Direct Photons - A Short Introduction

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for Quark Matter Studies in Heavy Ion Collisions

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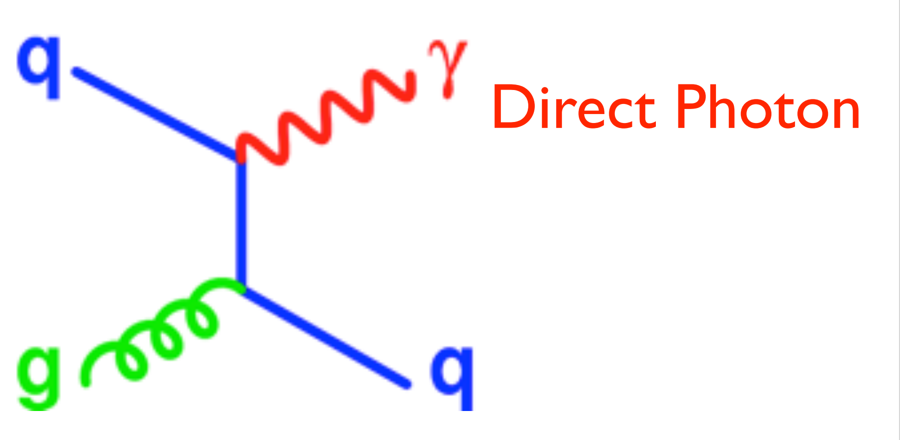
Outline

- Part I:
  - Introduction
  - Direct Photons in p+p and A+A
  - Measuring Direct Photons
- Part II:
  - Results in p+p Collisions
  - Results in A+A Collisions
    - Measurements with “real” photons
    - The internal conversion method
    - Using conversion in the detector material
  - Direct photon flow

Definition and Challenges

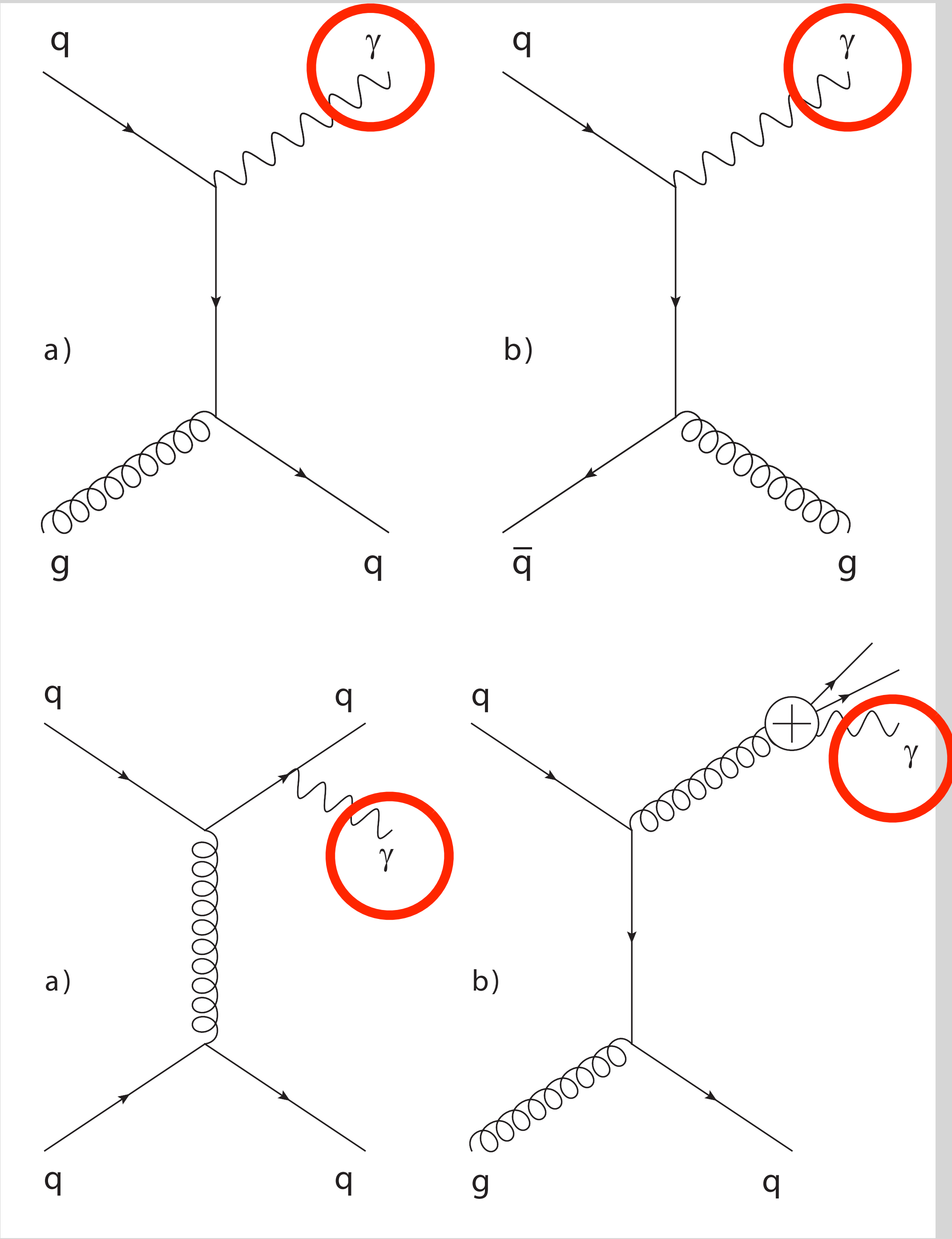
- Direct photons are
  - Photons not coming from decays (experimentalists view I)
  - Photons that are isolated (experimentalists view II)
  - Photons that are created directly in hard scattering processes (a possible theorists view)



- The measurement is challenging
  - Large background from decay photons
    - $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, and more
  - Finding isolated photons in large background in A+A
  - Experimental problems due to small opening angle of decay photons, π^0 (η) decay photons merge into one detector signal

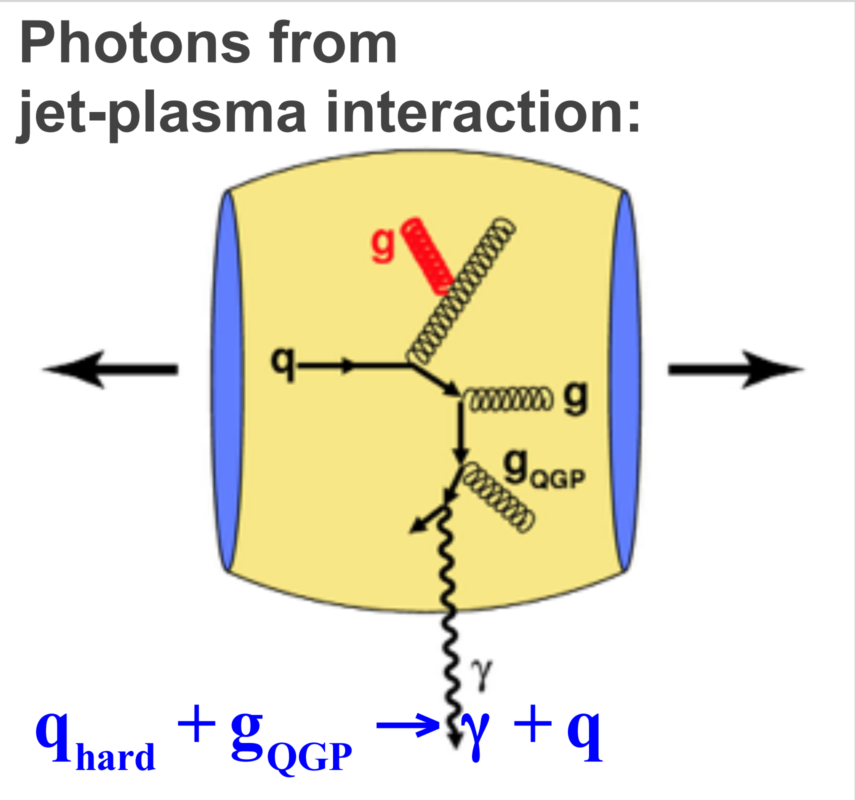
Direct Photons in p+p Collisions

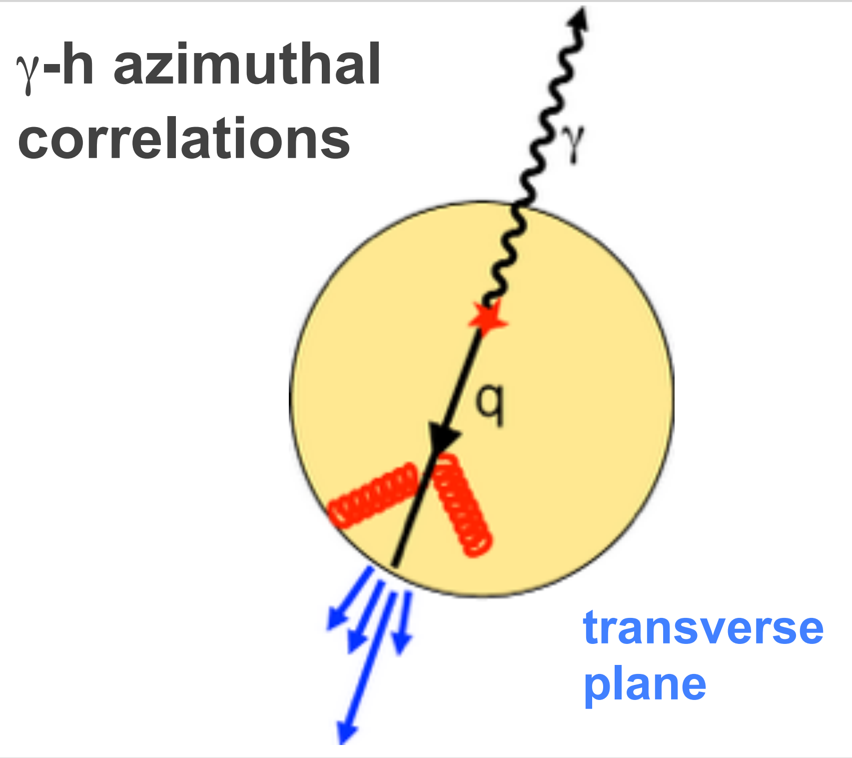
- In the late 1970's: direct photons suggested point-like charged objects within hadrons
- Different production processes
  - Top row: Quark-gluon Compton scattering (a), quark-antiquark annihilation (b)
  - Bottom row: bremsstrahlung (a), jet fragmentation (b)
- Test of QCD, processes well described
- Current focus: Constrain gluon distribution functions
  - Quark-gluon Compton scattering at leading order, unlike DIS and Drell-Yan



Direct Photons in Au+Au Collisions - why?

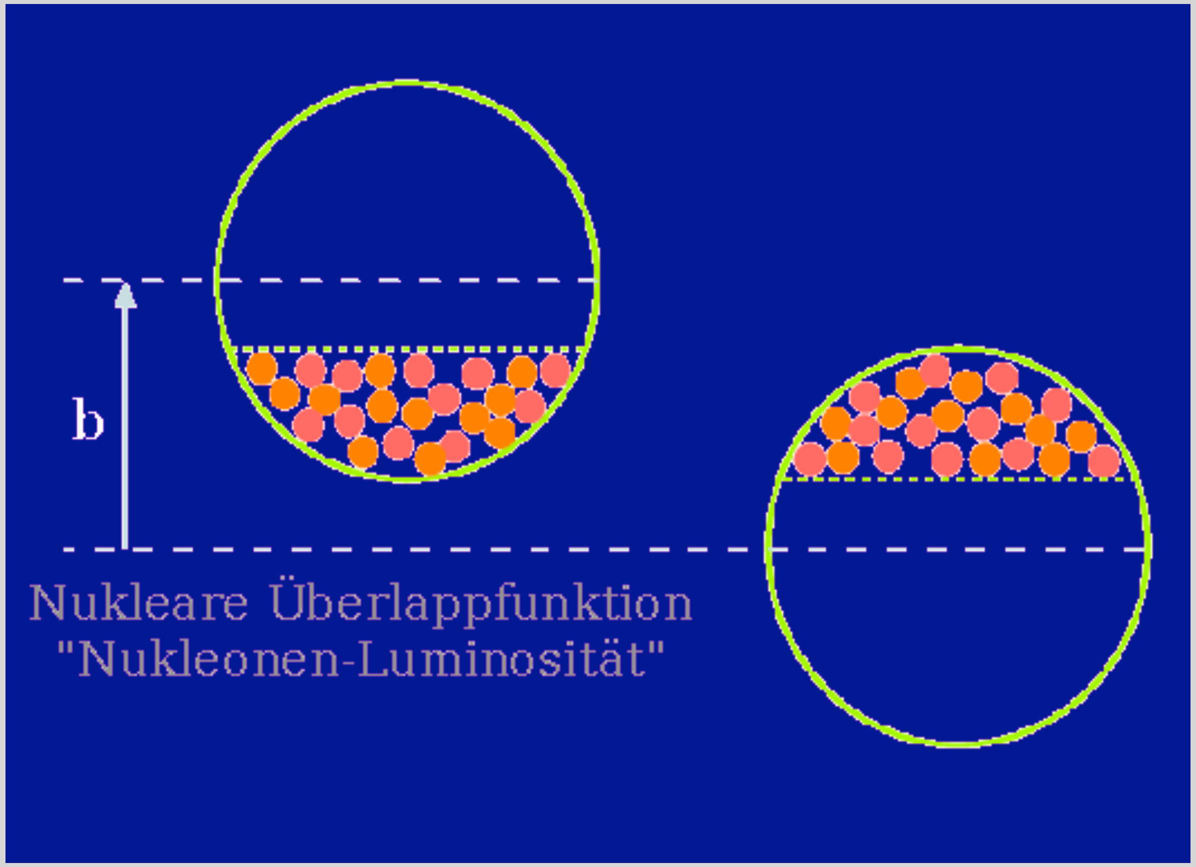
- Photons do not interact strongly and leave the medium (mostly) unaffected
- Different p_T regions give different information
  - Low p_T (< 4 GeV/c): thermal photons, measure the temperature of the fireball
  - Intermediate p_T (between ~2 and 6 GeV/*c*): are there other sources from within the QGP (e.g. from jet-plasma interaction)?
  - High p_T (> 6 GeV/*c*): Point like scaling for hard processes?
- Measure direct-γ - hadron angular correlations
  - In *p*+*p* access to fragmentation functions
  - In A+A, photon defines parton (jet) energy





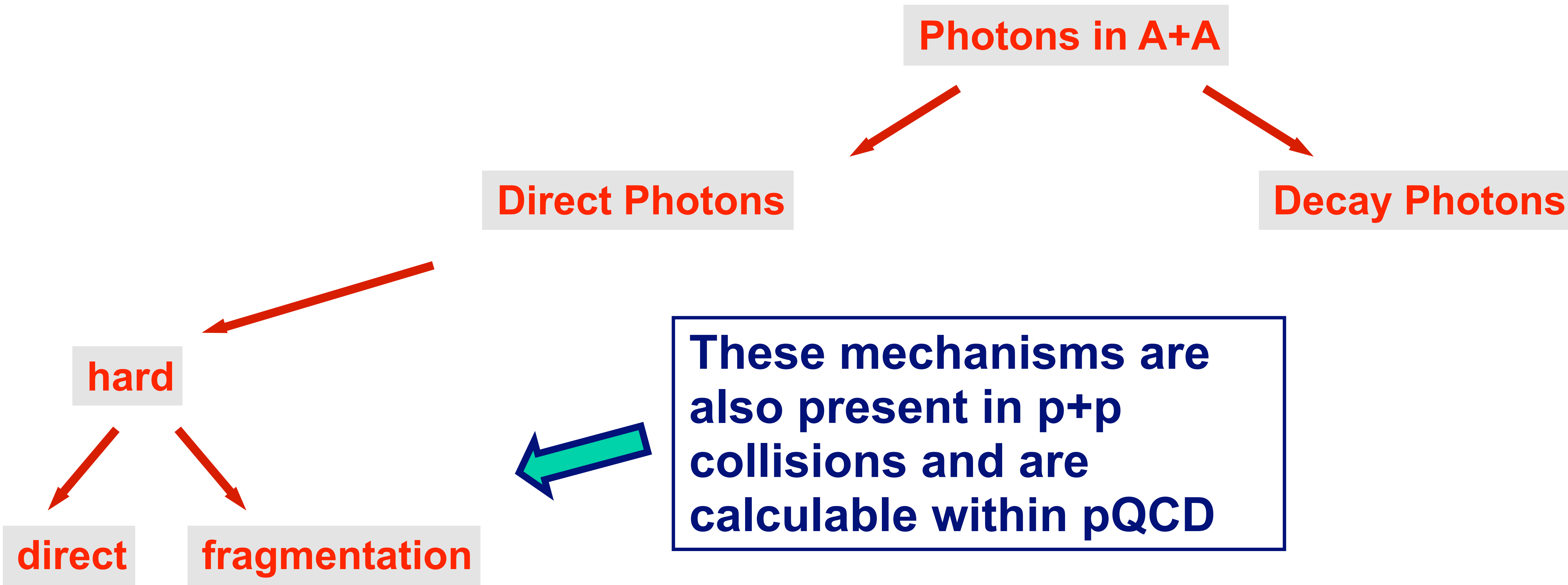
Quantify Nuclear Effects: The Nuclear Modification Facotr

- Measure to quantify nuclear effects in A+A collisions
- Compare A+A with scaled *p*+*p* collisions
- Number of binary nucleon-nucleon collisions (N_{coll}) from simulations
- R_{AA} „contains“ both initial and final state effects
  - Initial state: Cronin, nuclear shadowing, ..
  - Final state: Jet quenching



$$R_{AA} = \frac{d^2N_{AA}{}^{\eta}/dydp_T}{N_{coll}d^2N_{pp}{}^{\eta}/dydp_T}$$

Known and Presumed Photon Sources in A+A



Known and Presumed Photon Sources in A+A

Photons in A+A

Direct Photons

Decay Photons

hard

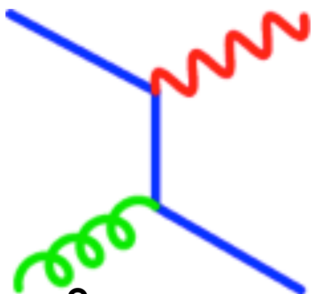
direct

fragmentation

Hard direct photons:
direct component
(“prompt” photons)

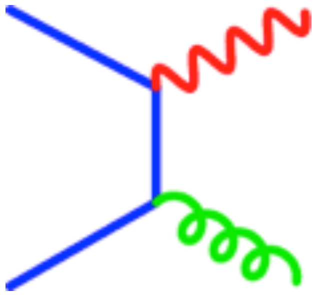
Compton

$$q + g \rightarrow \gamma + q$$



Annihilation

$$q + \bar{q} \rightarrow \gamma + g$$



Known and Presumed Photon Sources in A+A

Photons in A+A

Direct Photons

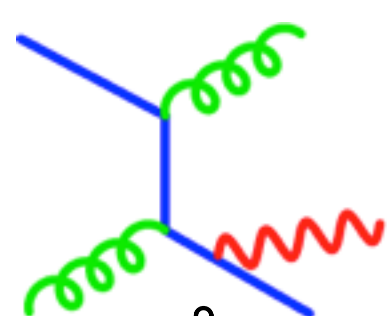
Decay Photons

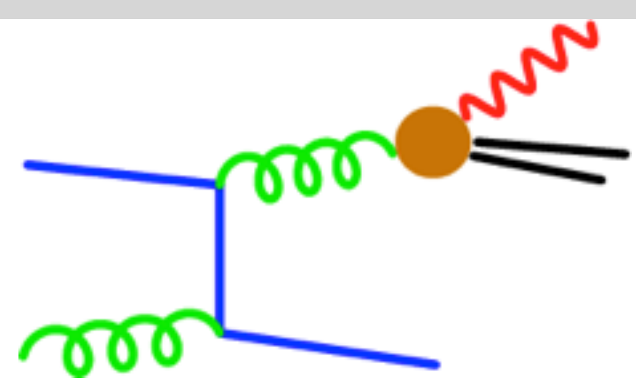
hard

direct

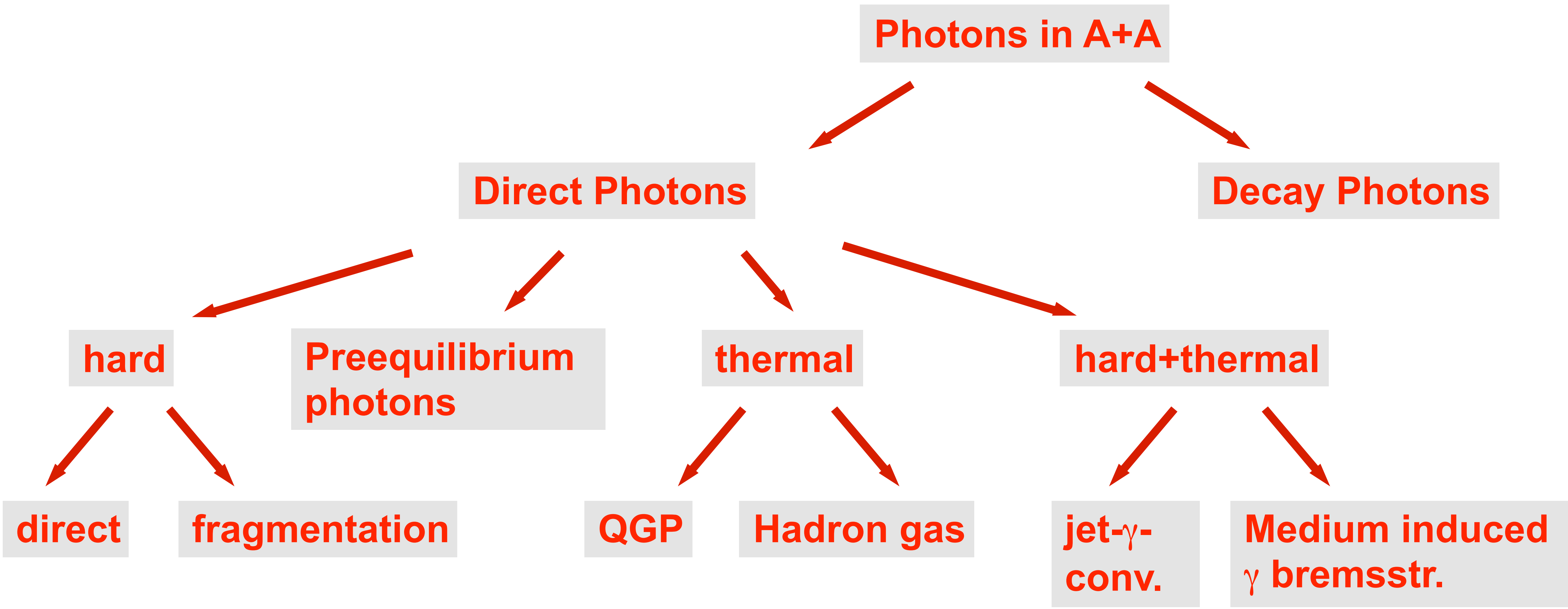
fragmentation

Hard direct photons:
bremsstrahlung / fragmentation component

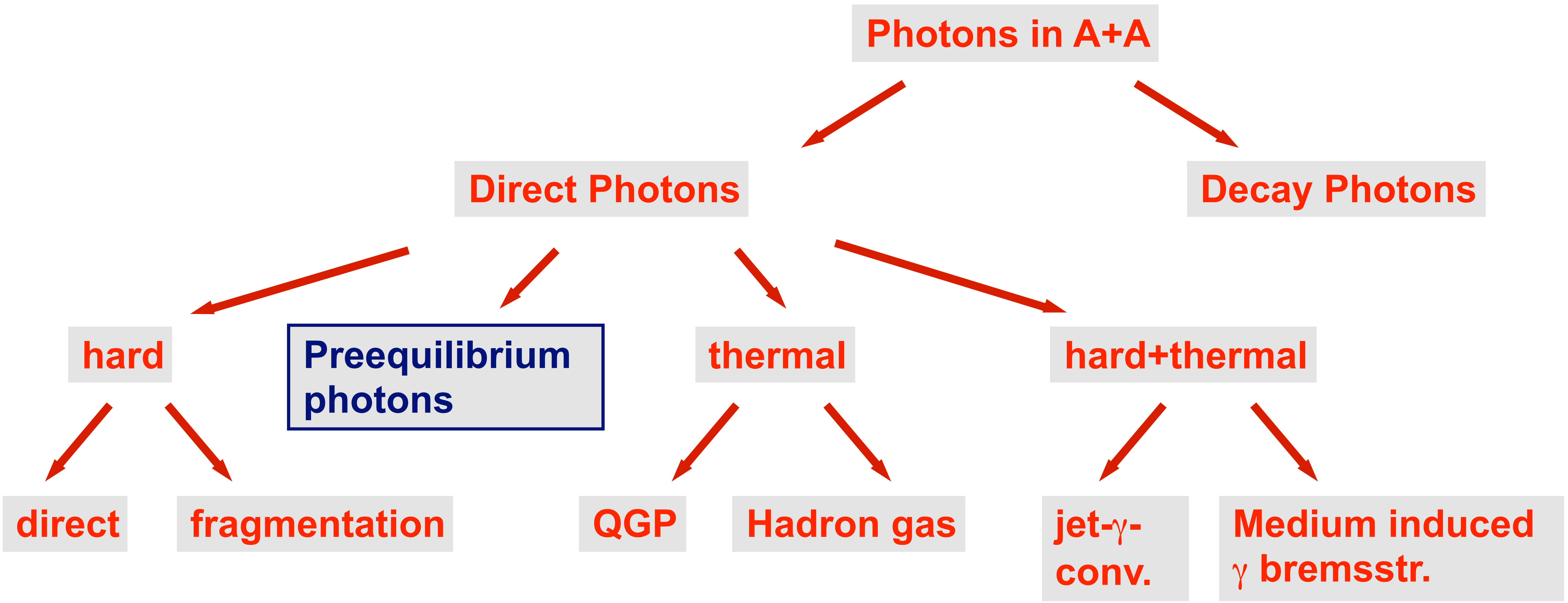




Known and Presumed Photon Sources in A+A



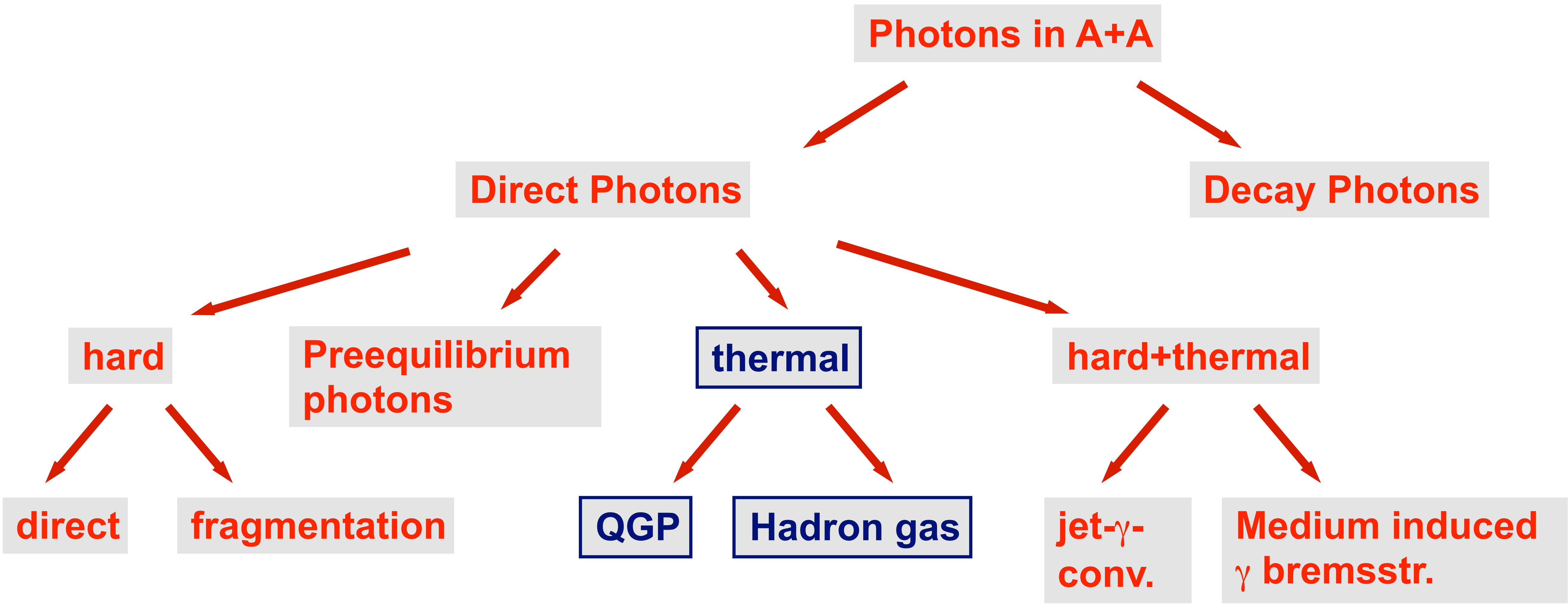
Known and Presumed Photon Sources in A+A



Preequillibrium photons

- Produced through rescattering of the primarily produced partons prior to thermalization
- Difficult to treat theoretically

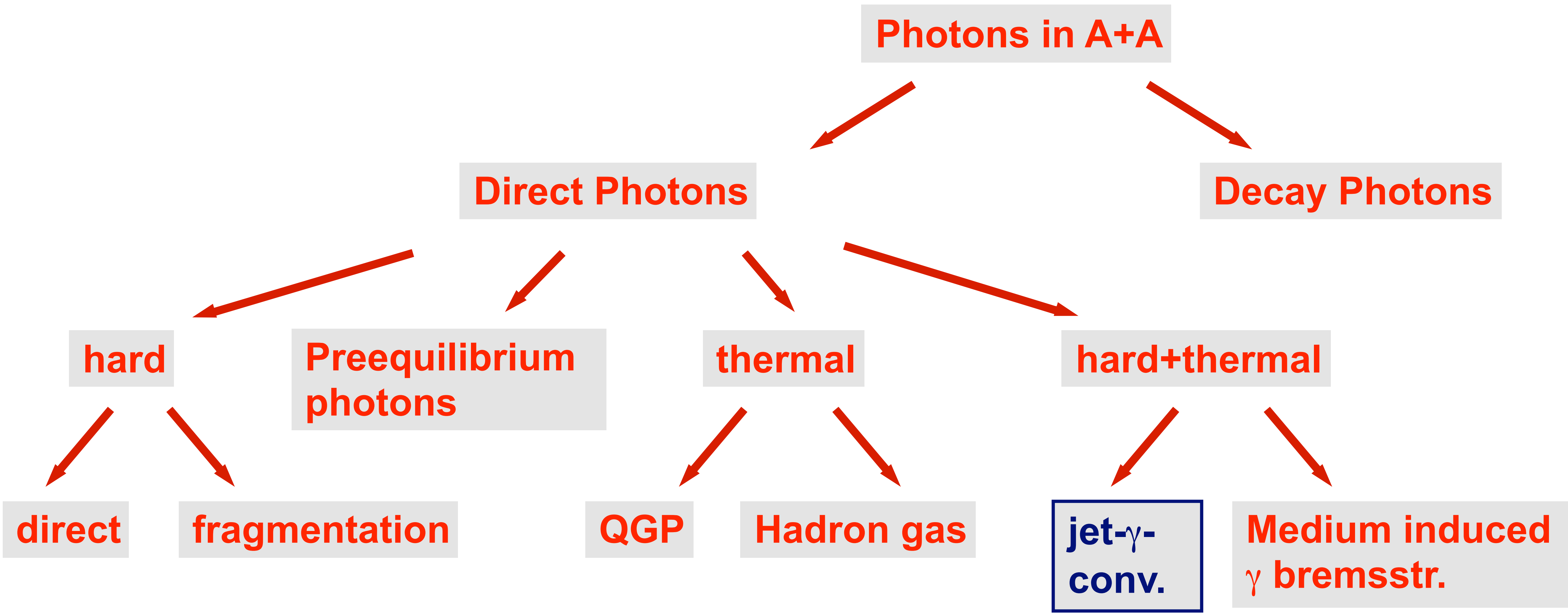
Known and Presumed Photon Sources in A+A



Thermal photons

- Reflect temperature of the system, produced over entire evolution
- Significant direct photon source only at low p_T

Known and Presumed Photon Sources in A+A



Hard+thermal:
Jet-Photon-Conversion

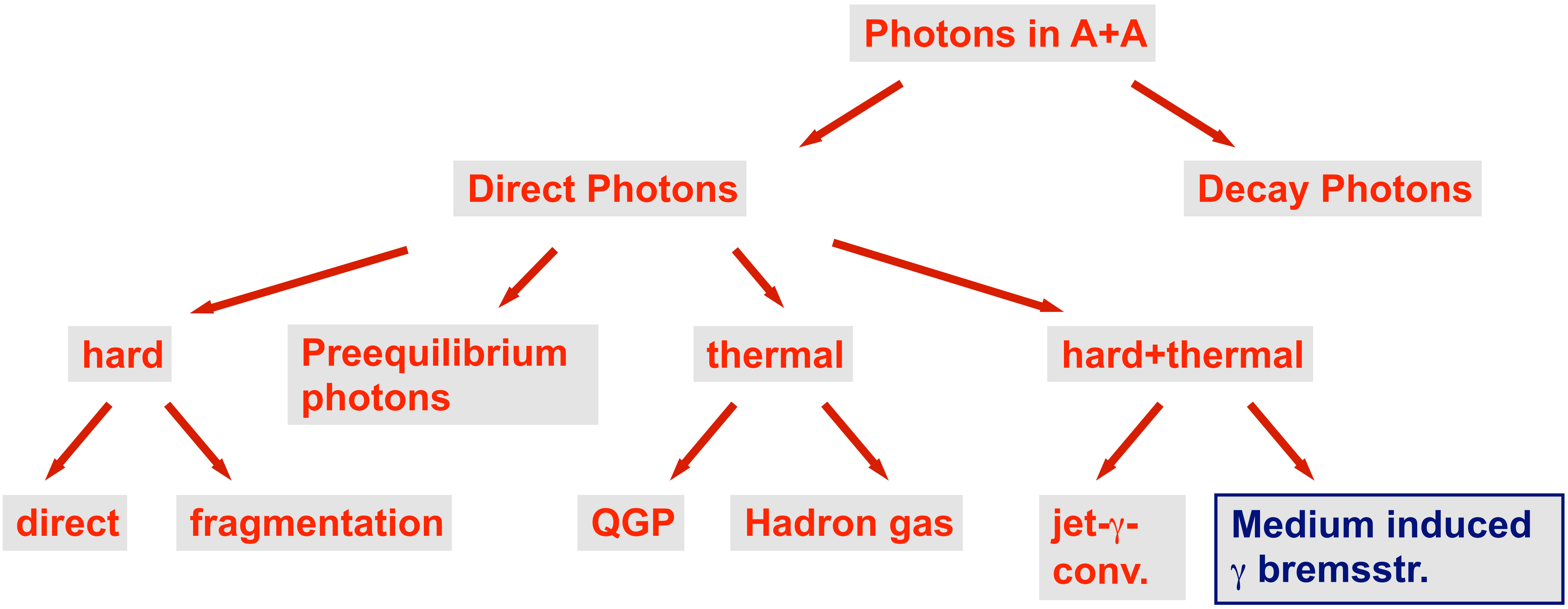
Interaction of parton from hard scattering with soft parton

$$\sigma_{\mathrm{jet}-\gamma-\mathrm{conv}} \sim \delta^3 \left(p_{\mathrm{jet}} - p_{\gamma}\right)$$

$$\mathbf{q}_{\mathrm{hard}} + \mathbf{g}_{\mathrm{QGP}} \rightarrow \gamma + \mathbf{q}$$

$$\mathbf{q}_{\mathrm{hard}} + \bar{\mathbf{q}}_{\mathrm{QGP}} \rightarrow \gamma + \mathbf{g}$$

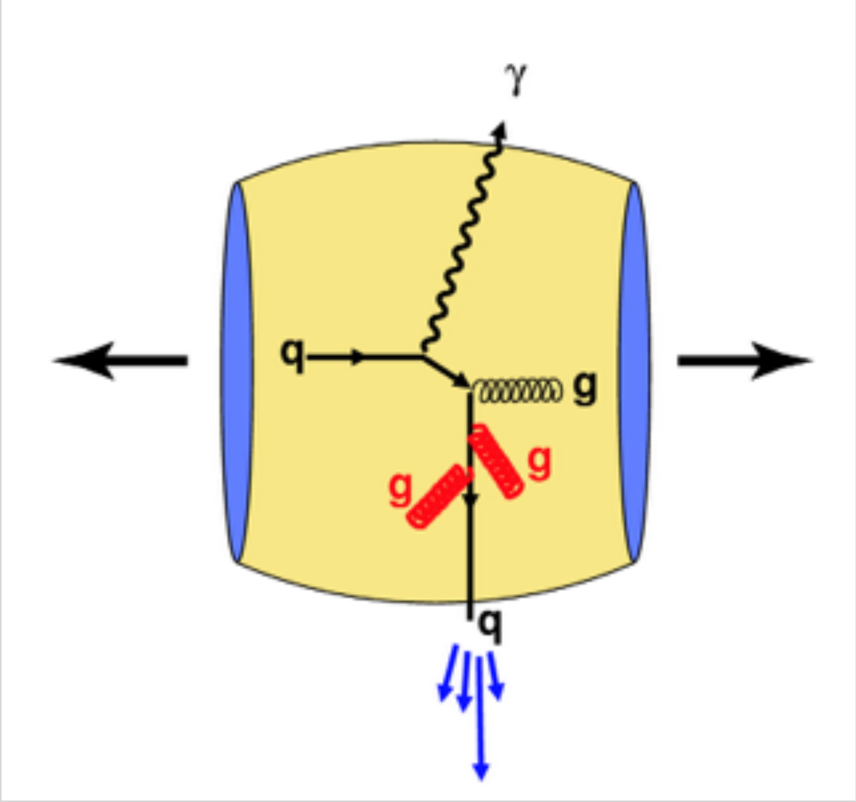
Known and Presumed Photon Sources in A+A



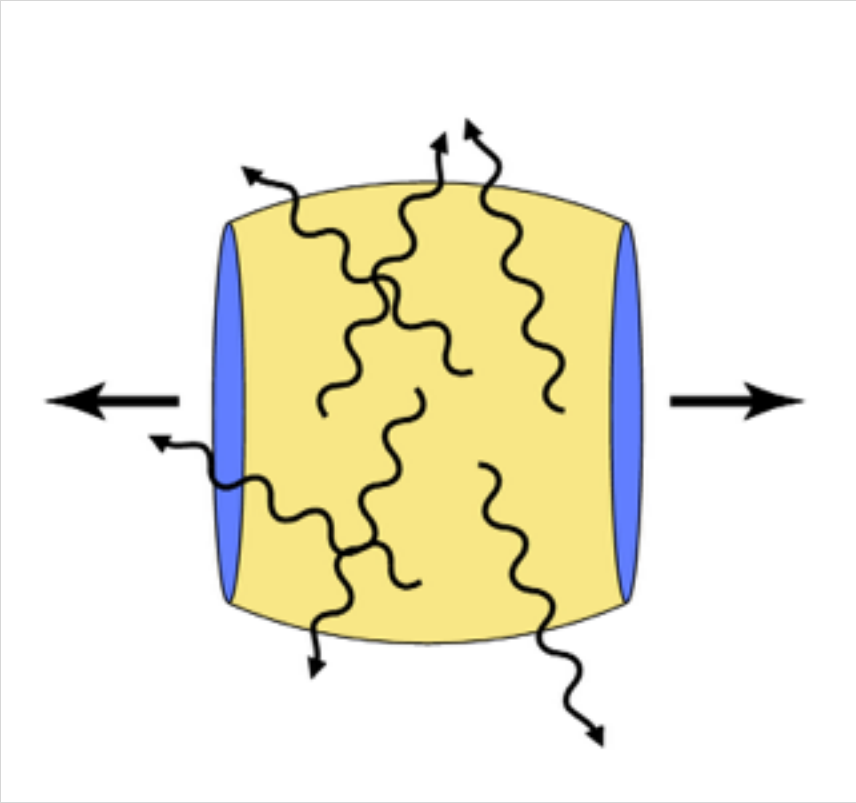
Medium induced photon bremsstrahlung

- Due to multiple scattering of quarks in the medium
- Different theoretical predictions, likely rather small contribution

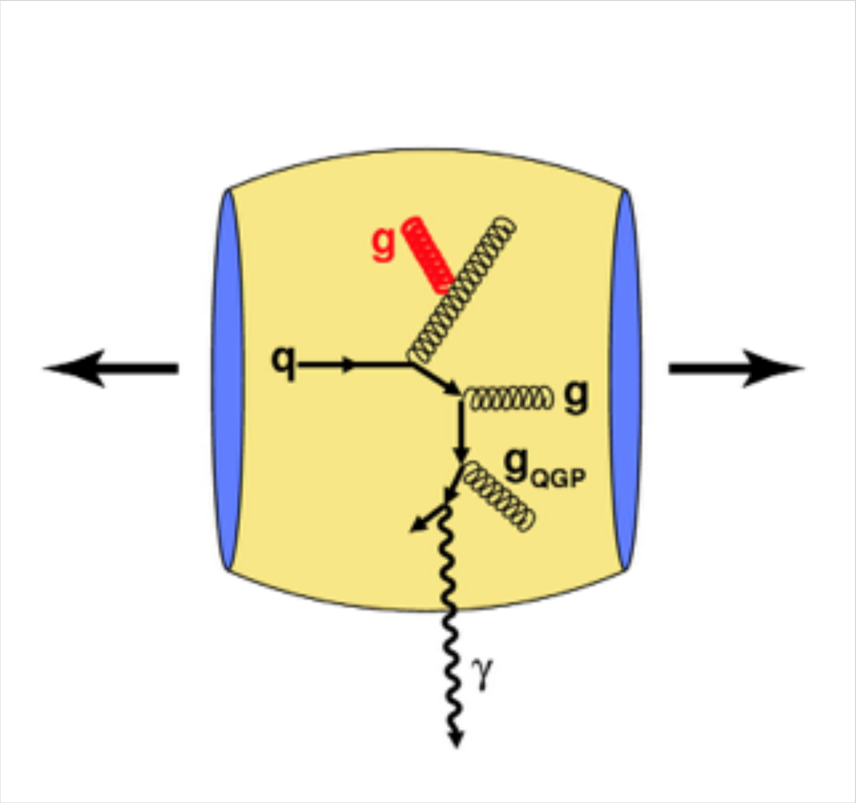
Summary: Direct Photons in A+A Collisions - Hard, Thermal, Hard+Thermal



Hard photons

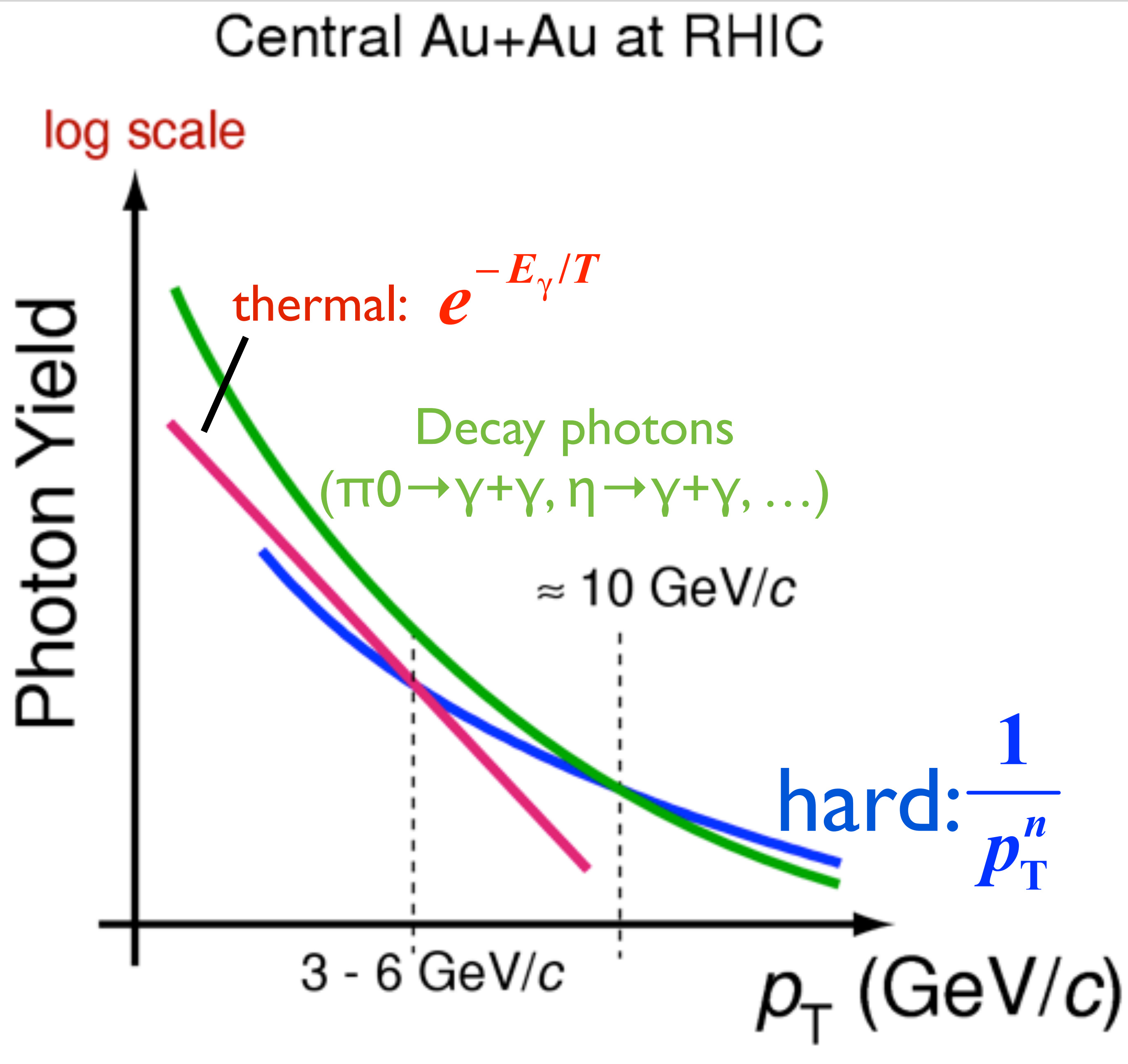


Thermal photons



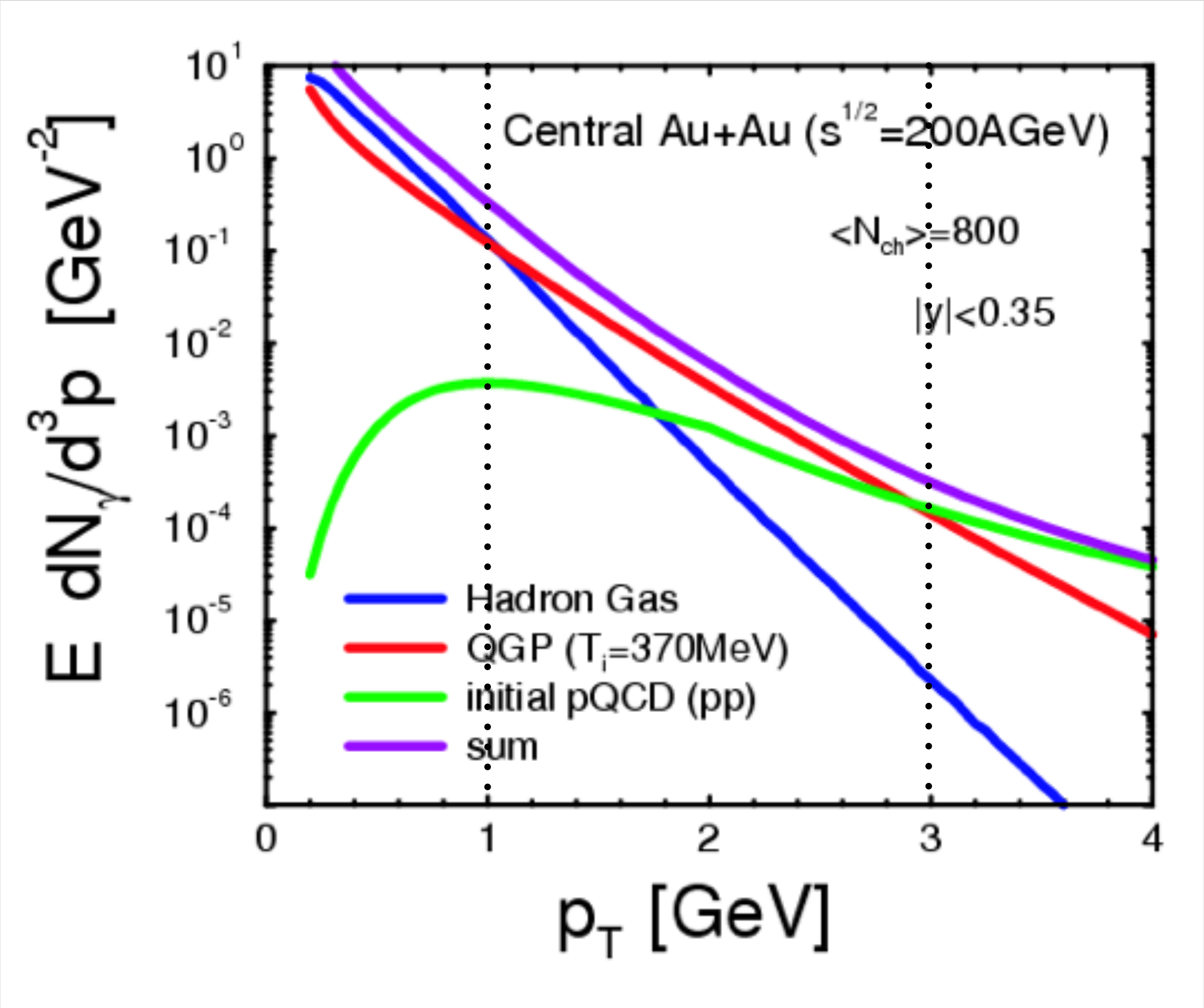
Photons form jet-plasma interaction

Schematic Photon Spectrum in A+A



- Thermal photons expected to be a significant contribution below p_T ~ 3 GeV/*c*
- Hard photons dominant direct photon source for p_T > ~ 6 GeV/*c*
- Jet-photon conversion might be significant contribution below p_T ~ 6 GeV/*c*
- Experimental challenge: Subtraction of decay photon background

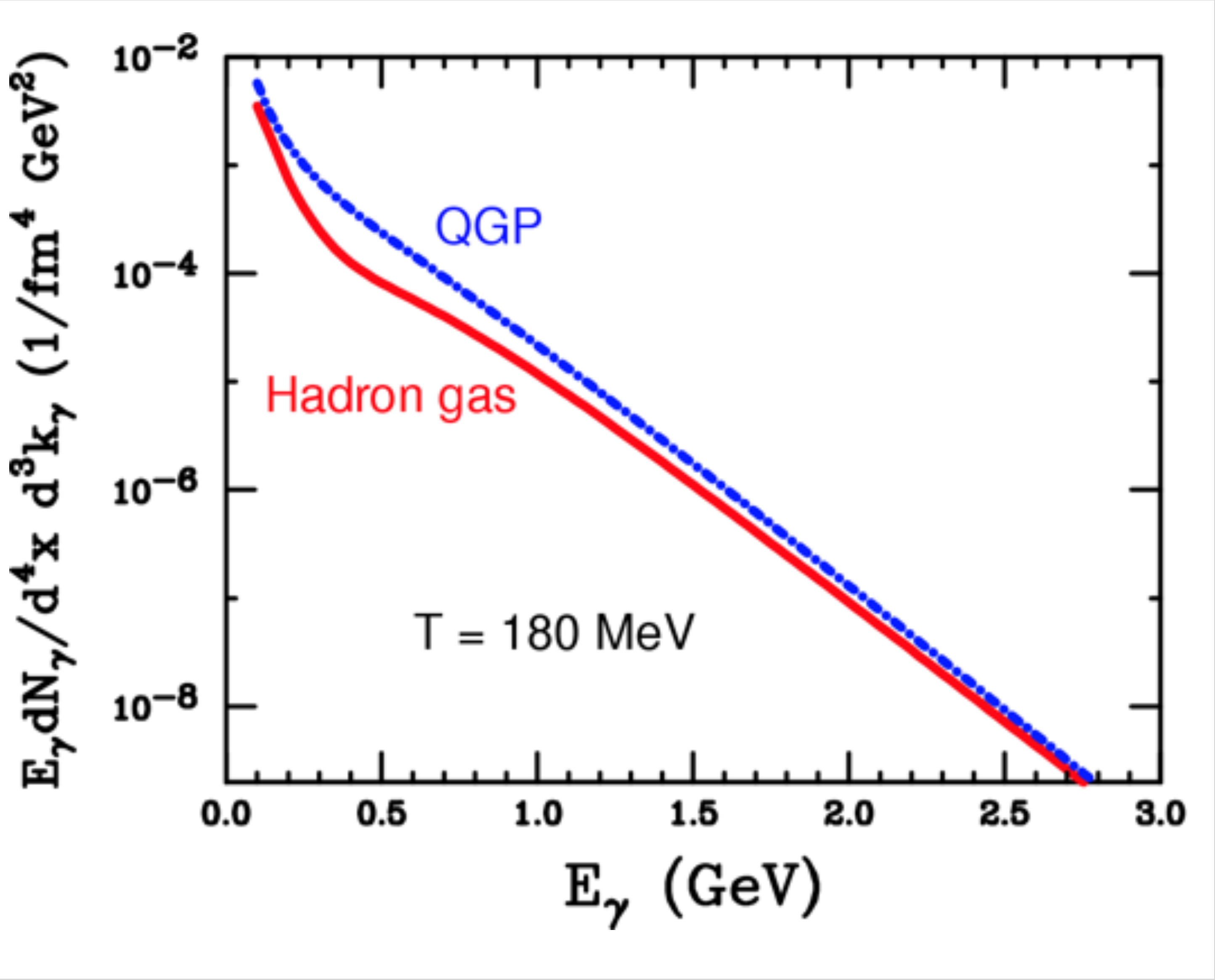
Direct Photons in A+A: Realistic Calculation



Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004

- Window for thermal photons from QGP in this calculation: p_T = 1 - 3 GeV/c

Photon Rates in HG and QGP



- Final thermal photon spectrum:
  QGP and HG photon rates convoluted with space-time evolution of the reaction
- Very similar thermal photon rates for QGP and hadron gas at same temperature T

QGP rates: Arnold, Moore, Yaffe (2001)
HG rates: Turbide, Rapp, Gale (2004)

Measuring Direct Photons: Method Overview

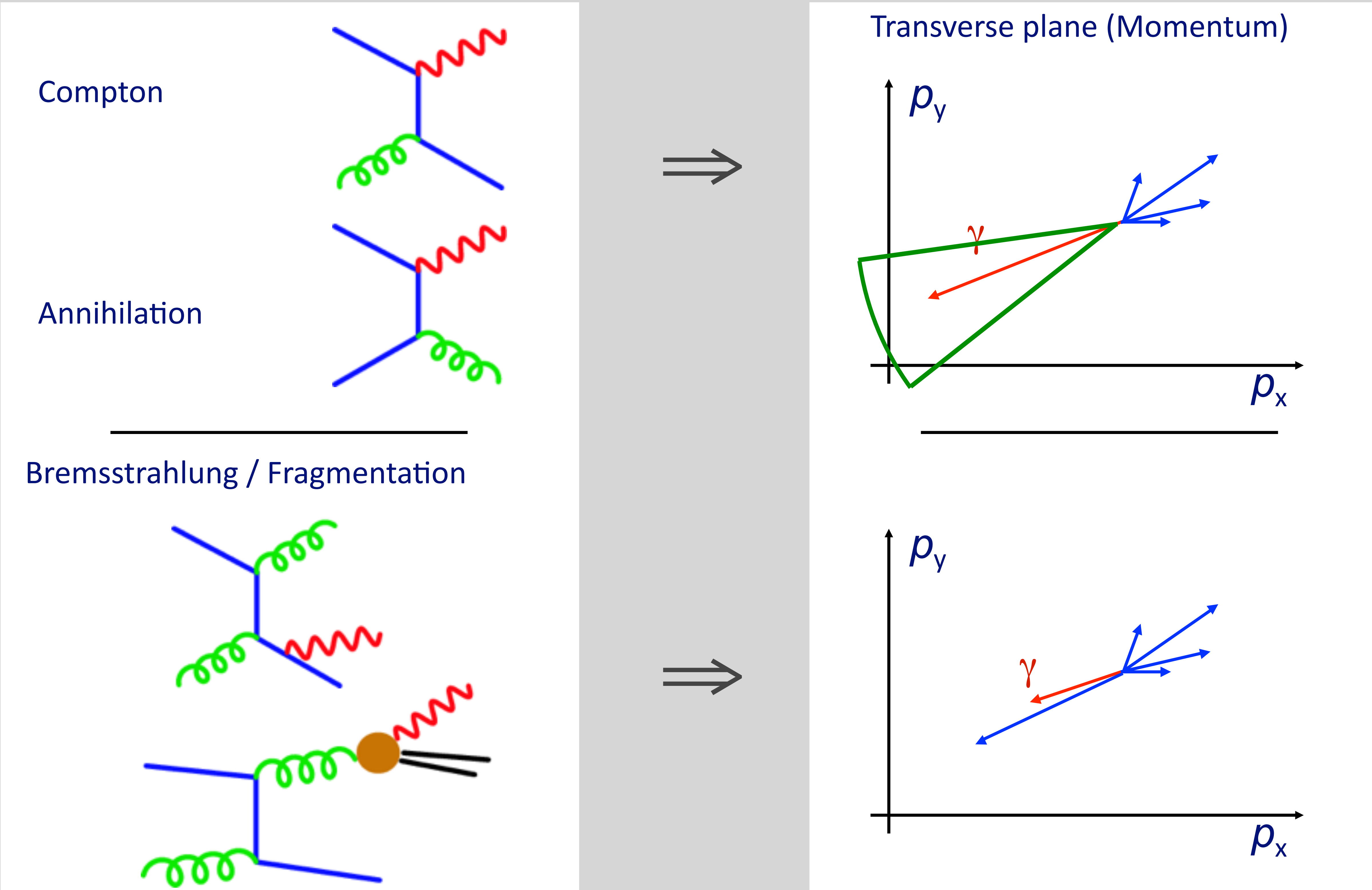
- Calorimeter measurement with isolation and shower shape cuts
  - Works best in p+p and at high p_T
- Statistical subtraction method
  - Measure inclusive photon spectrum and subtract decay photons from hadrons
    - Inclusive photons can be measured directly with calorimeters or indirectly through conversions into e^+e^- pairs
    - Decay photons come from simulations
- Tagging method
  - Remove decay photons by tagging decay photons, i.e. calculate if it can come from a decay

Direct Photon Measurement

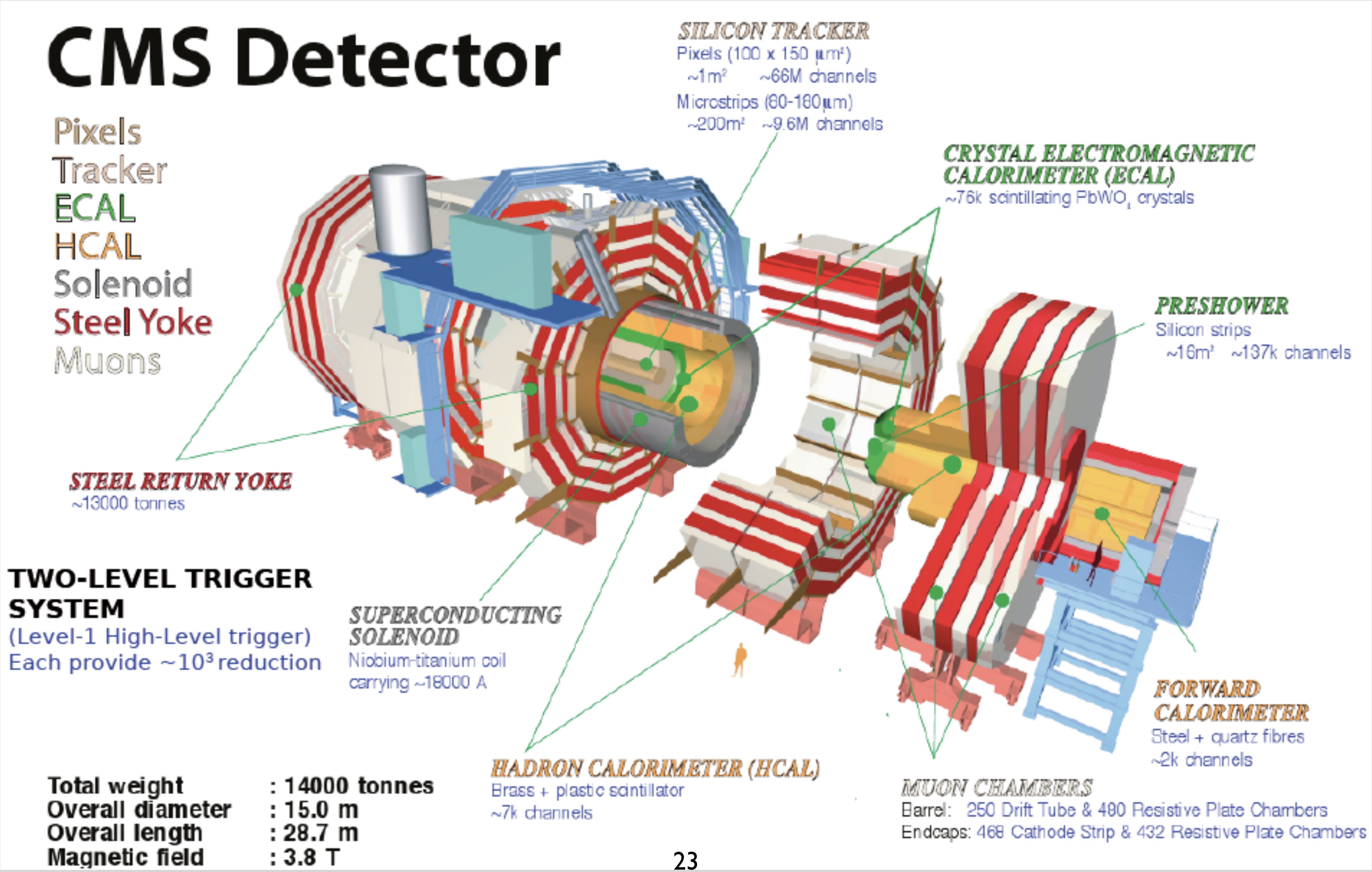
Isolation Cut

Isolation Cut: The Idea

Isolated direct photons:
Limit on transverse energy
in a cone around the photon



Example of an Isolated Photon Measurement: CMS Experiment



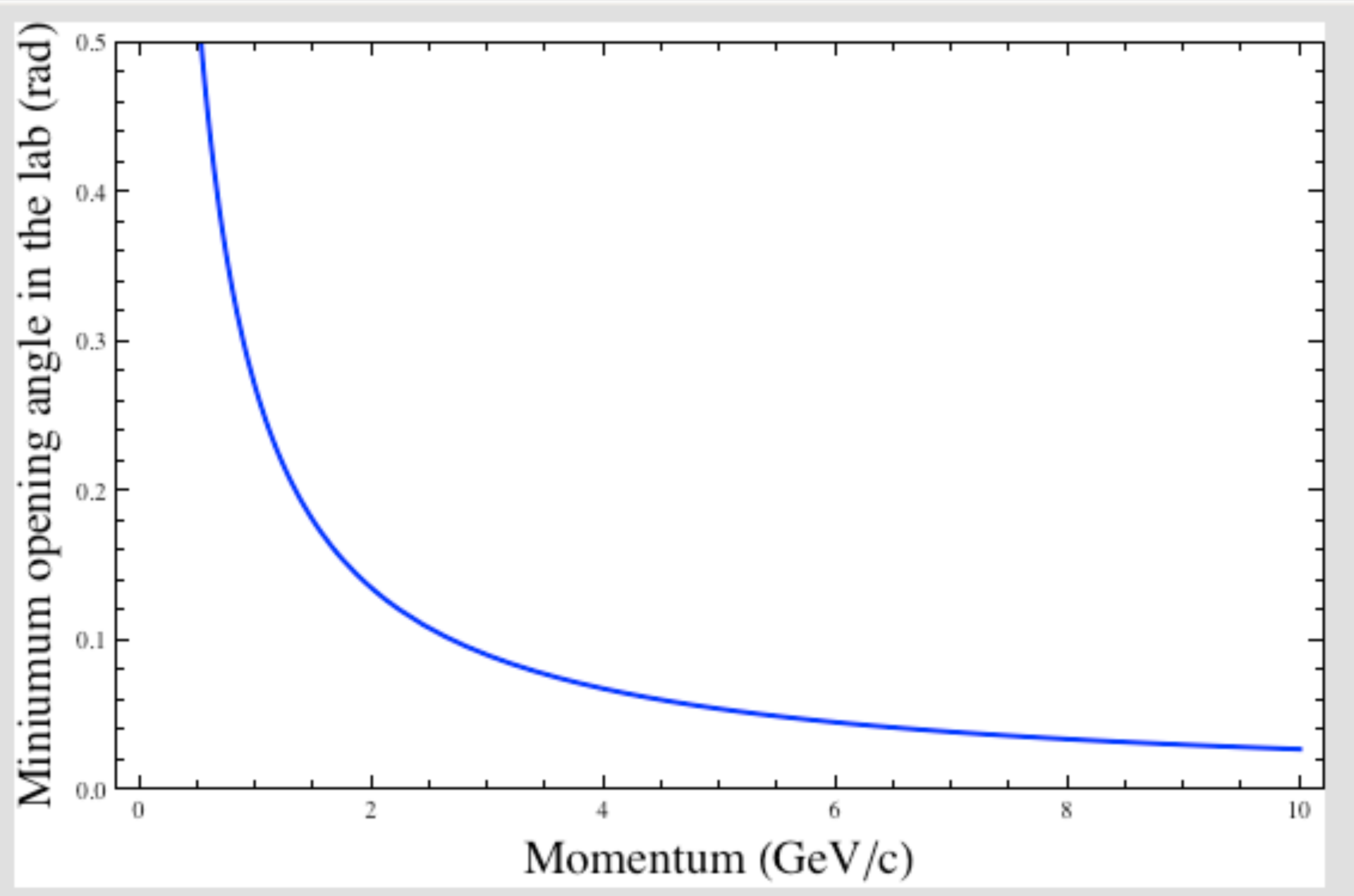
Isolation Cut Requirements at CMS

$$R^2 = (\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2$$

- Photon candidates must satisfy three isolation requirements that reject photons produced in hadron decays
  - IsoTRK < 2 GeV/*c* in 0.04 < R < 0.40, excluding a rectangular strip of $\Delta\eta \times \Delta\Phi$ = 0.015 0.400 to remove the photon's own energy if it converts into an e+e-
  - IsoECAL < 4.2 GeV (transverse energy in ECAL in 0.06 < R < 0.40, excluding again a central region for the photon)
  - IsoHCAL < 2.2 GeV (transverse energy in HCAL)
- These conditions remove the bulk of the photons from neutral meson decays

Opening Angle of π^0 Decay Photons

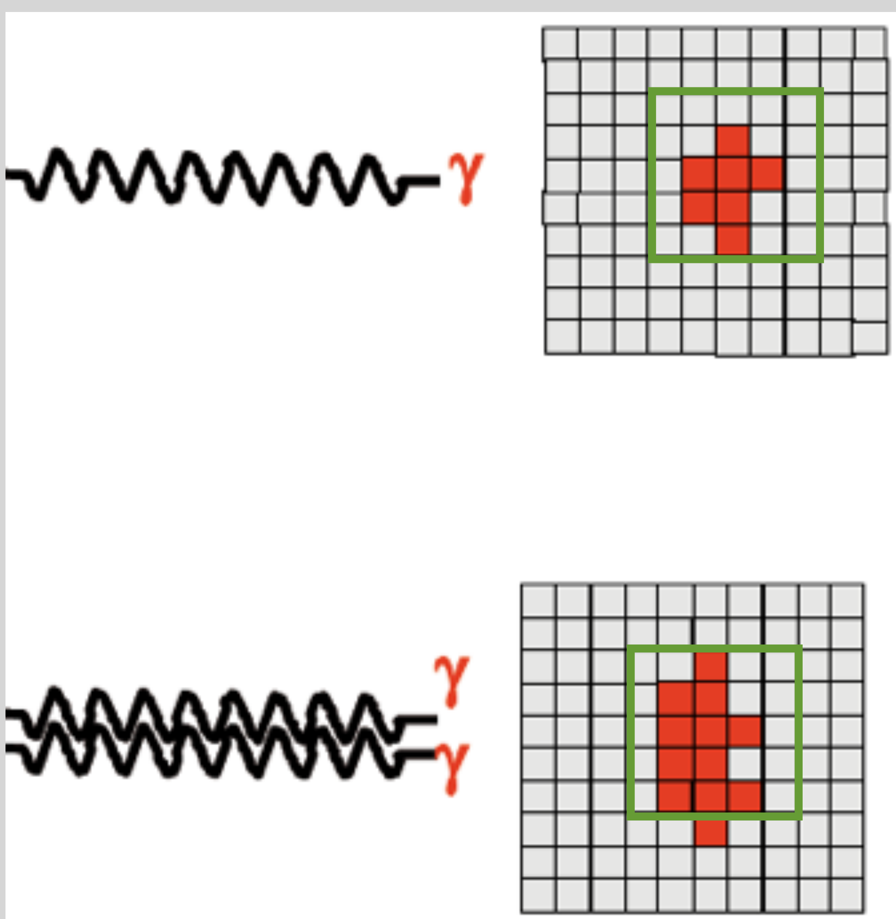
- At high momenta, the opening angle gets so small that decay photons might be reconstructed as one cluster on the calorimeter

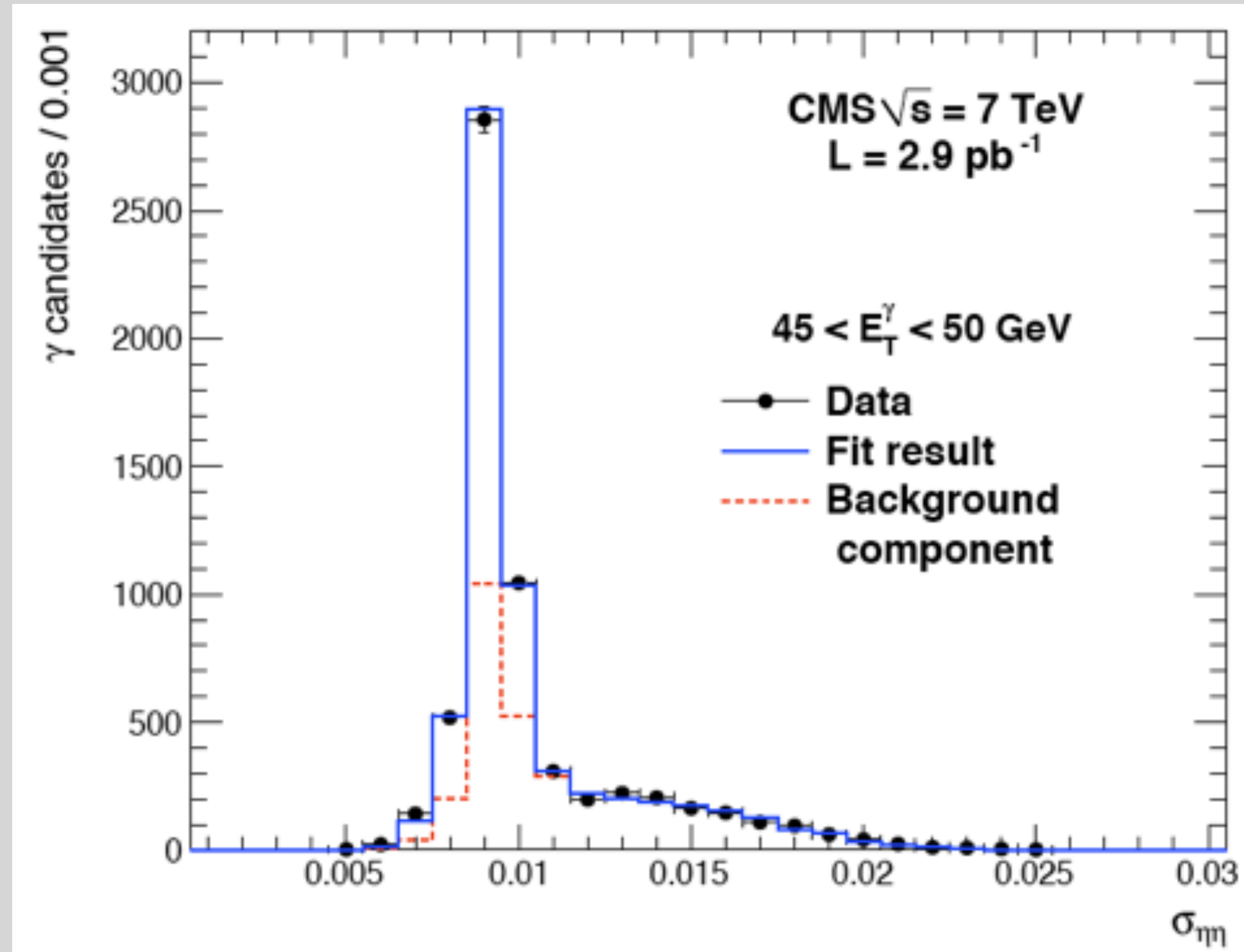


Signal Extraction

$$\sigma^2_{\eta\eta} = \sum_{i=1}^{25} w_i(\eta_i - \bar{\eta})^2 / \sum_{i=1}^{25} w_i$$

$$w_i = \max(0, 4.7 + \ln(E_i/E))$$





- Calculate shower width, use towers in a 5x5 window around highest energy tower
- Isolated photon yields extracted by fitting signal + background templates to measured shower width distribution
- Signal template from MC (Pythia + Geant)
- Background template determined in data-driven way

Statistical Subtraction

Measurement of Direct Photons with the Subtraction Method

- Get clean inclusive photon sample
  - Understand detector effects, calibrations, geometry
  - Subtract non photons
- Measure p_T spectrum of π^0 and η mesons with high accuracy
- Calculate number of decay photons per π^0
  - Done with Monte-Carlo
  - m_T scaling for (η), η', ω, …
- Finally:
  Subtract decay background from inclusive photon spectrum

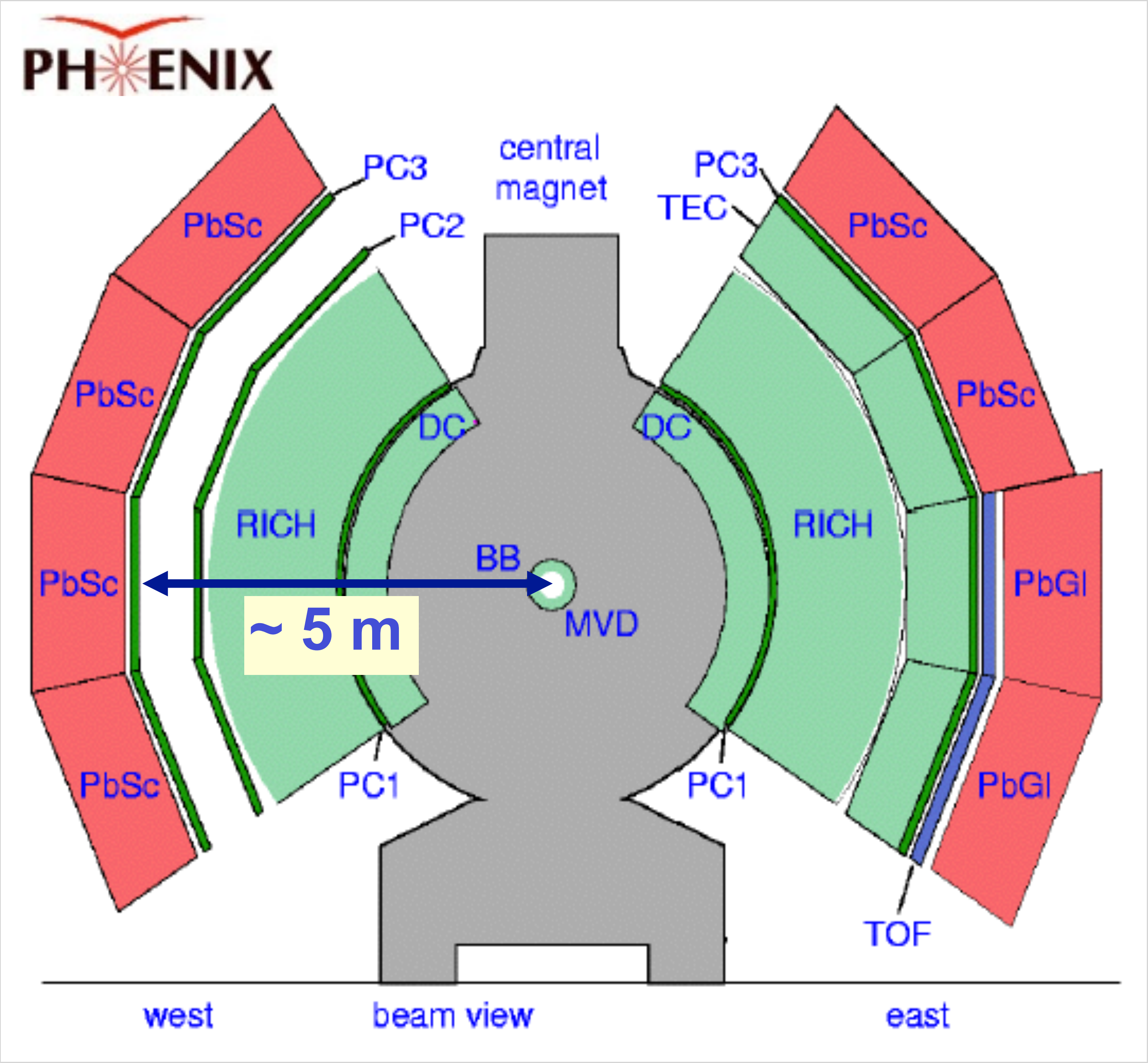
Pocket formula:

$$\frac{1}{p_T}\frac{dN_{\pi^0}}{dp_T} \propto 1/p_T^n$$

$$\Rightarrow \frac{\gamma_{\pi^0}^{\text{decay}}}{\pi^0} = \frac{2}{n-1} \approx \textbf{0.28 at RHIC}$$

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$

PHENIX: Photon and Electron Detectors



Pseudorapidity coverage :
$|\eta| < 0.35$

- EMCal:
  PbSc (6 sectors) + PbGl (2 sectors)
- PbSc :
  - Highly segmented lead scintillator sampling calorimeter
  - Module size:
    5.5 cm x 5.5 cm x 37 cm
- PbGl:
  - Highly segmented lead glass Cherenkov calorimeter
  - Module size:
    4.0 cm x 4.0 cm x 40 cm
- Ring Imaging Cherenkov Detector (RICH):
  - Electron identification (together with E/p matching in EMCal)
  - No signal for charged pions with p < 4.6 GeV/c

Direct Photons: Statistical Subtraction Method

$$\pi^0 \rightarrow \gamma + \gamma, \;\; \eta \rightarrow \gamma + \gamma, \;\; \ldots$$

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{backgr}} = \left(1 - \frac{\gamma_{\text{backgr}}/\pi^0}{\gamma_{\text{inclusive}}/\pi^0}\right) \cdot \gamma_{\text{inclusive}}$$

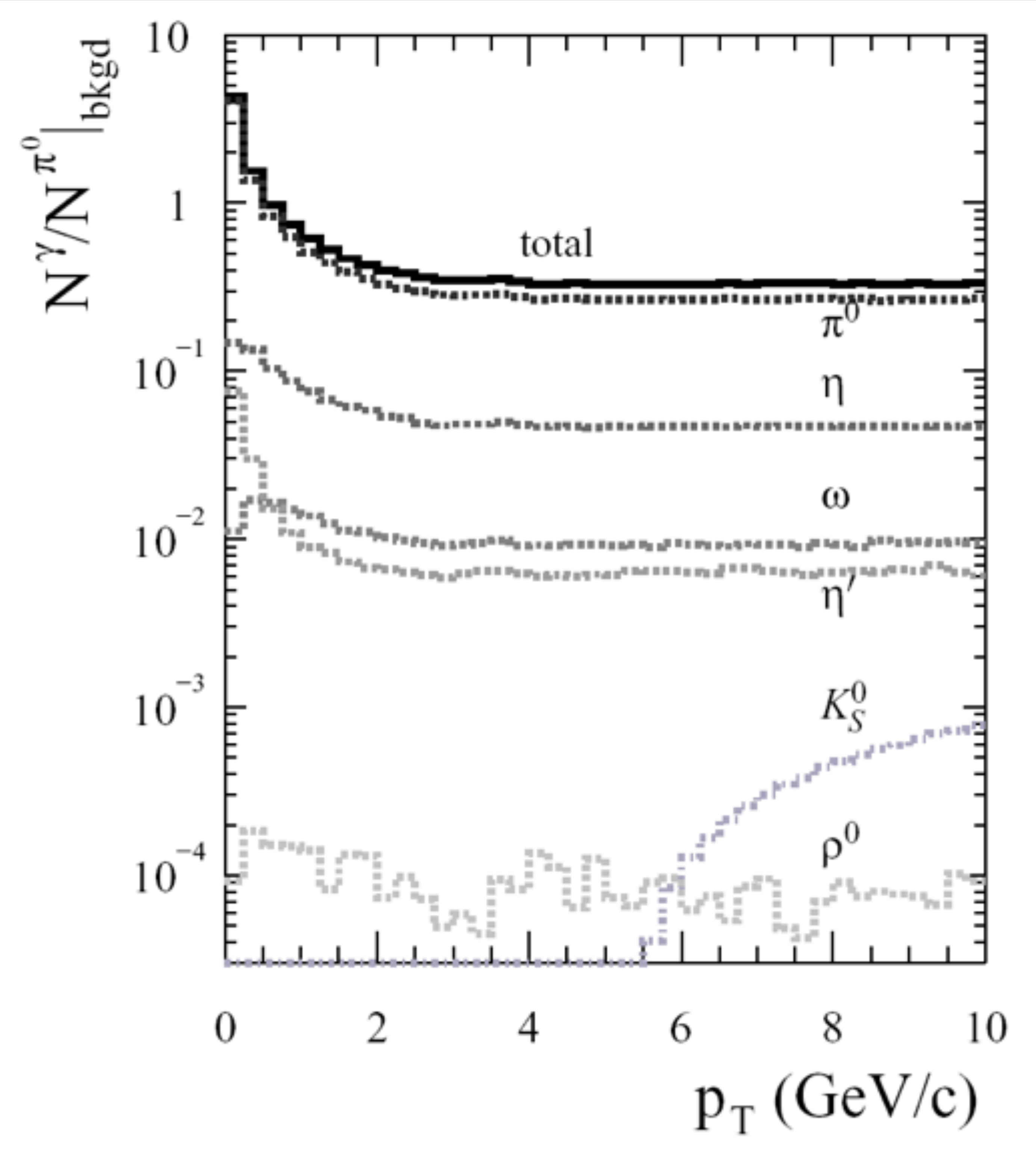
$$= (1 - 1/R) \cdot \gamma_{\text{inclusive}}$$

with $$R = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{backgr}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{backgr}}} \equiv \frac{(\gamma_{\text{inclusive}}/\pi^0)_{\text{meas}}}{(\gamma_{\text{backgr}}/\pi^0)_{\text{calc}}}$$

Calculated based on measured π^0 and η spectrum (includes ω, η', … decays)

Systematic errors (e.g. energy scale non-linearity) partially cancel in this ratio

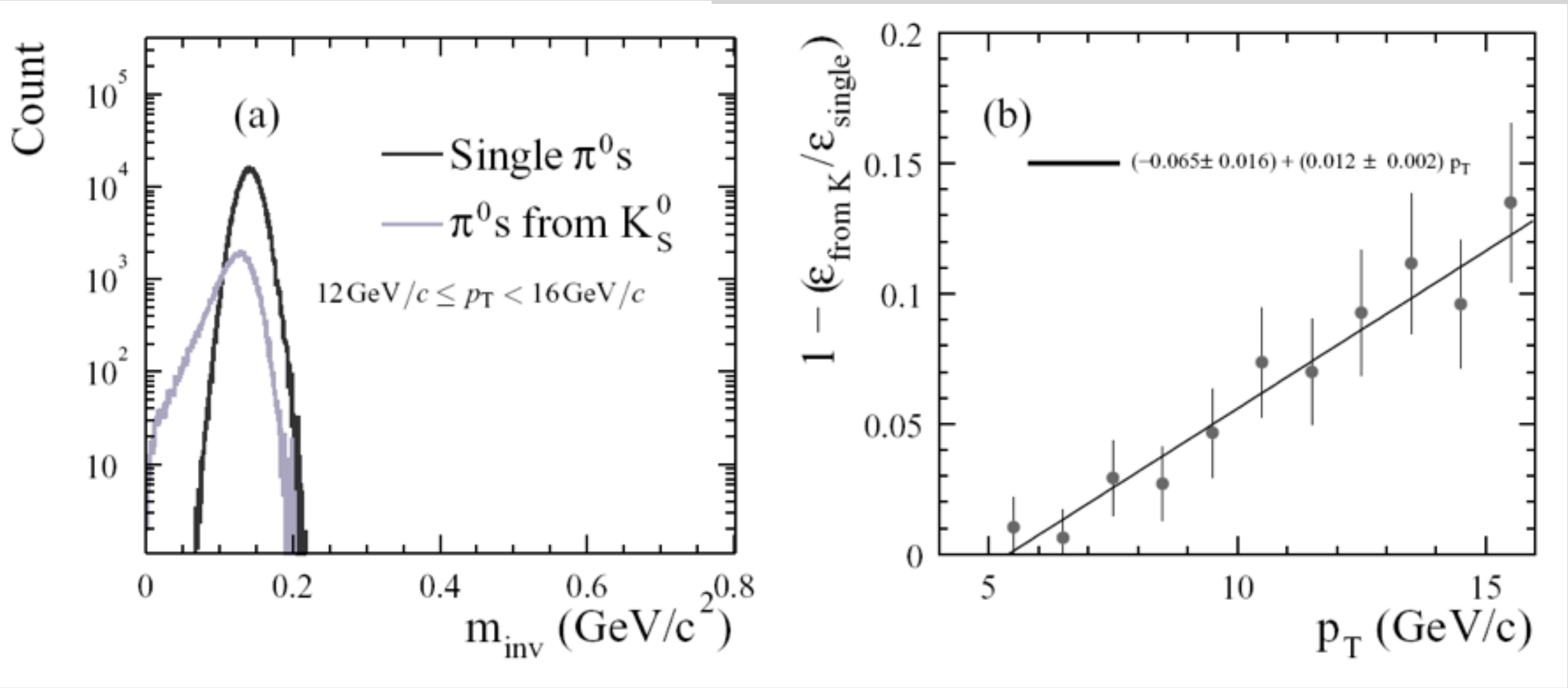
Decay Photon Calculation



- Simple Monte Carlo code
- Pure kinematics (no detector simulation needed)
- ~96% of the background photons from π^0 and η decays
- Simulation based on measured π^0 input spectra
- Decay photons from other mesons are based on m_T scaling to the π^0 spectrum

Background Photons from $K_s^0 \rightarrow \pi^0 + \pi^0$

Probability to miss a π^0 from $K_s^0 \rightarrow \pi^0+\pi^0$ in the π^0 reconstruction due to displaced decay vertex



$$K_s^s : c\tau_0 = 2.67\,\mathrm{cm} \qquad L_{\mathrm{lab}} = v \cdot \gamma \cdot \tau_0 = \beta \cdot \gamma \cdot \tau_0 \cdot c \qquad \beta \cdot \gamma = \frac{p}{mc}$$

p	1 GeV	5 GeV	10 GeV
⟨	5,37 cm	26,9 cm	53,7 cm

Formula for Fully Corrected Inclusive Photon Spectrum

Fraction of neutral background (neutron, anti-neutrons)

Fraction of charged clusters

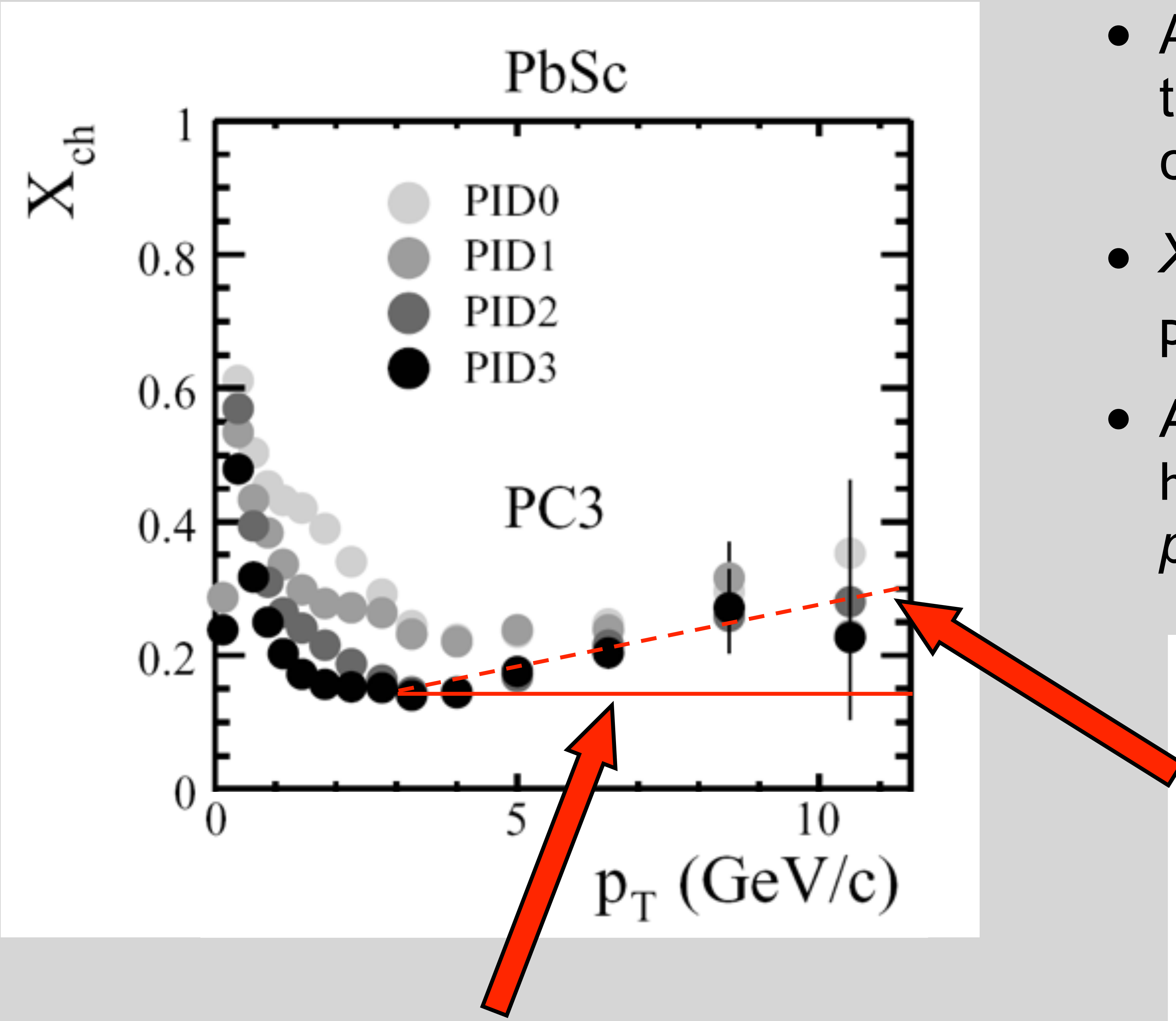
$$\left.\frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{incl}} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{in}}} \cdot \frac{(1 - X_{\mathrm{n\bar{n}}}) \cdot (1 - X_{\mathrm{ch}})}{\varepsilon_\gamma \cdot a_\gamma \cdot c_{\mathrm{conv}}} \cdot \frac{\Delta N_{\mathrm{cluster}}}{\Delta p_{\mathrm{T}} \Delta y},$$

efficiency

acceptance

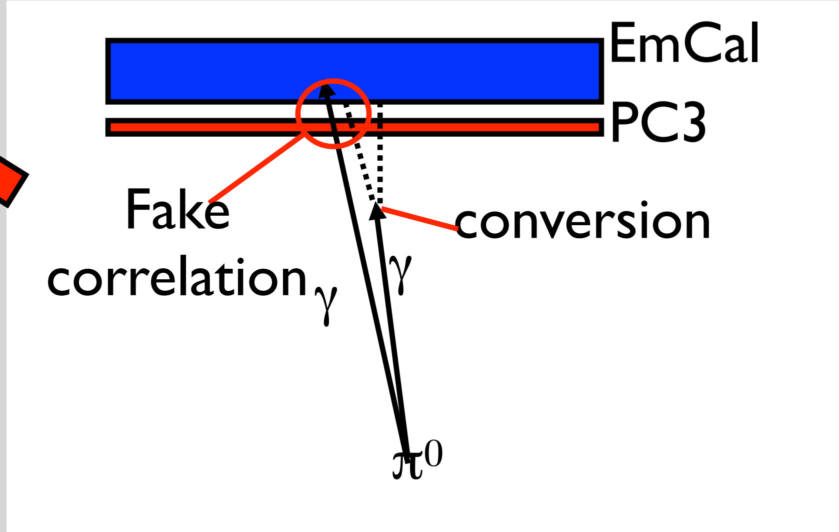
photon conversion

Charged Background: X_{ch}



final correction

- At low p_T, mostly hadrons that are reconstructed in the calorimeter
- $X_{ch} > 0$ at high p_T largely due to photon conversion
- Artificial decay photon-charged hit (PC3) correlations at high p_T:



Neutral Background: X_{nn}

- Background from neutrons and antineutrons needs to be simulated (GEANT for detector response to neutrons)
- Input neutron and anti-neutron spectra not measured, but "determined" from measured proton and anti-proton spectra

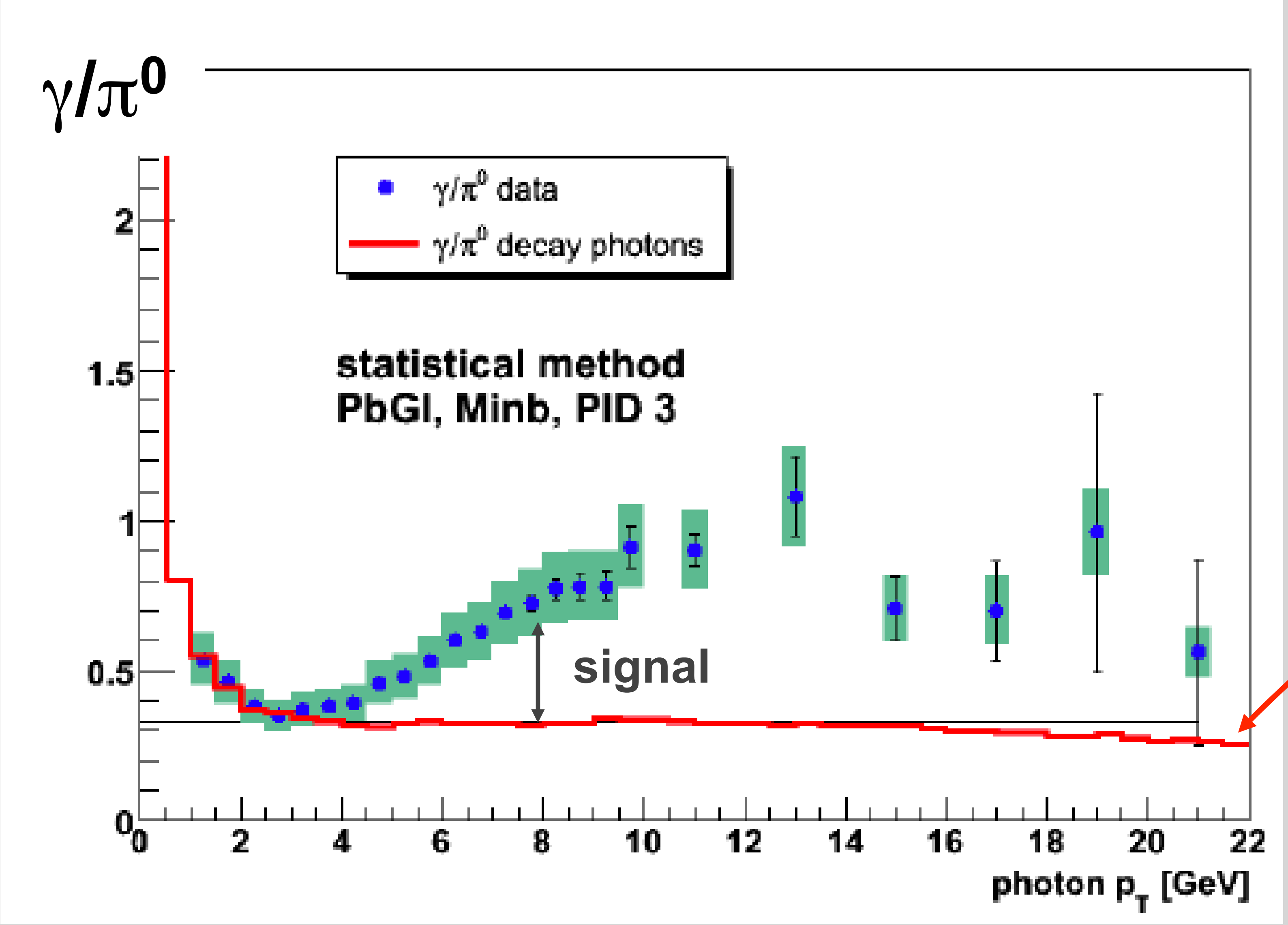
$$\left.\frac{d^2N}{dp_T dy}\right|_{\bar{n}} = \left.\frac{d^2N}{dp_T dy}\right|_{\bar{p}},$$

$$\left.\frac{d^2N}{dp_T dy}\right|_{n} = \left.\frac{d^2N}{dp_T dy}\right|_{\bar{p}} + \left(\left.\frac{d^2N}{dp_T dy}\right|_{p} - \left.\frac{d^2N}{dp_T dy}\right|_{\bar{p}}\right)\frac{A-Z}{Z}$$

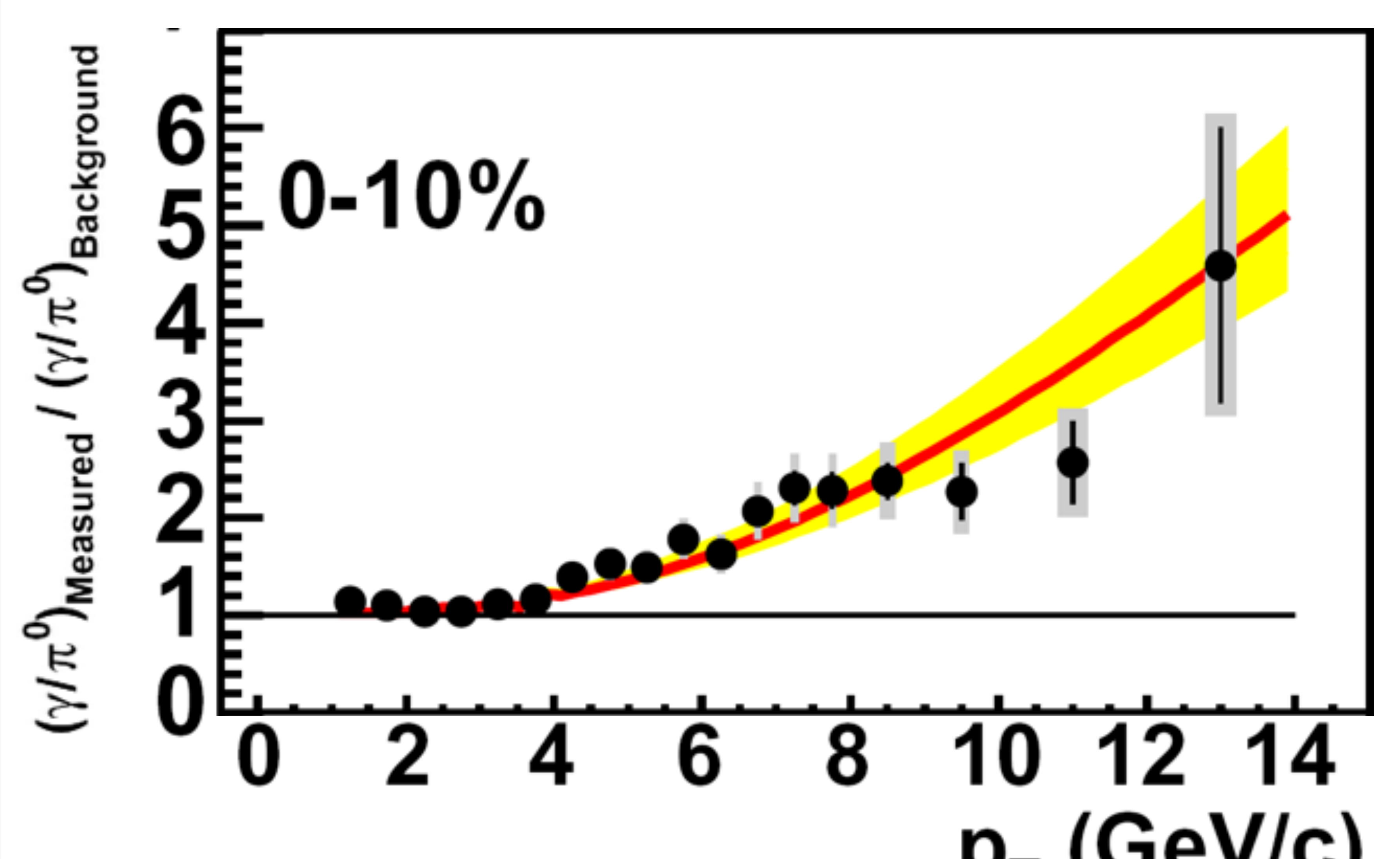
The γ/π^0 ratio

remember $$R = \frac{\gamma_{\text{inclusive}}}{\gamma_{\text{backgr}}} = 1 + \frac{\gamma_{\text{direct}}}{\gamma_{\text{backgr}}} \equiv \frac{(\gamma_{\text{inclusive}}/\pi^0)_{\text{meas}}}{(\gamma_{\text{backgr}}/\pi^0)_{\text{calc}}}$$

Calculated based on measured π^0 und η spectra



Result: Double Ratio



PHENIX, Phys.Rev.Lett.94:232301,2005

Multiply Inclusive Photon Spectrum by the double ratio to obtain direct-photon spectrum (and add systematic uncertainties of the inclusive photon spectrum which cancelled in the double ratio)

Systematic Uncertainties of the Subtraction Method

- π^0 measurement
  - Peak extraction
  - Yield correction (acceptance + efficiency)
  - Energy scale

- Inclusive photon measurement
  - Non-photon background
  - Yield correction (acceptance + efficiency)
  - Energy scale

Many systematic uncertainties of π^0 and photon measurements are highly correlated!

Non-linearity in the EM calorimeter is also crucial. It is vital, for instance, that two 3 GeV photons have the identical response as one 6 GeV photon.

Systematic Uncertainties (Example: PHENIX, Run-2 Au+Au)

	PbGl		PbSc	
π^0 error source	3.25 GeV/c	8.5 GeV/c	3.25 GeV/c	8.5 GeV/c
Yield extraction	8.7%	7%	9.8%	7.2%
Yield correction	12%	12%	12%	13.3%
Energy scale	13.8%	14.1%	10.5%	11.4%
Total systematic	20.3%	19.5%	18.8%	19%
Statistical	10.6%	32.5%	3%	13.1%
γ error source				
Non-γ correction	2.4%	2.4%	[illegible]	[illegible]
Yield correction	10.2%	12.0%	[illegible]	[illegible]
Energy scale	15.7%	13.7%	[illegible]	[illegible]
Total systematic	18.9%	18.4%	16.5%	16.7%
Statistical	1.2%	14.1%	0.7%	7.9%
γ/π^0 syst.	10.4%	10.4%	10.6%	10.6%
γ/π^0 stat.	10.7%	37.7%	3%	16.5%

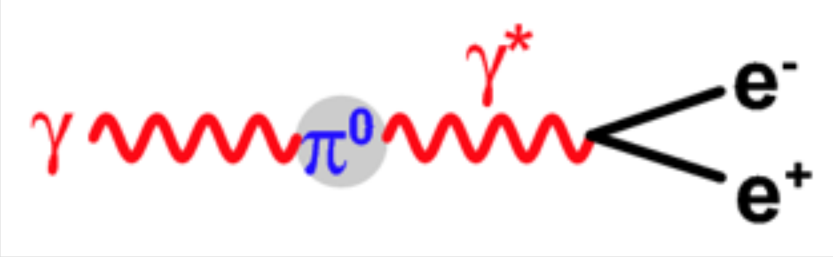
Treating photon and π^0 measuments as independent would yield a 28% systematic uncertainty for γ/π^0

PHENIX, Phys.Rev.Lett.94:232301,2005

Internal Conversion

Direct Photons via Internal Conversion

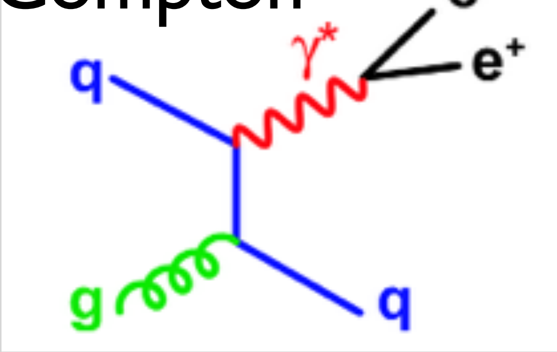
- Motivation:
  Measure in low p_T region where thermal photons are expected and calorimetric measurements are difficult
- Internal conversion
  - Any source of real photons also emits virtual photons
  - Well known example: π^0 Dalitz decay



  - Rate and m_{ee} distribution calculable in QED (Kroll-Wada formula)
- Hadron decays: $m_{ee} < M_{hadron}$
- Essentially no such limit for point-like processes, such as direct photons

Improve signal-to-background ratio by measuring e+e- pairs with $m_{ee} > \sim M_{pion}$

Compton



Kroll-Wada Formula

Number of virtual photons per real photon (in a given Δη Δφ ΔpT interval):

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

invariant mass of Dalitz pair

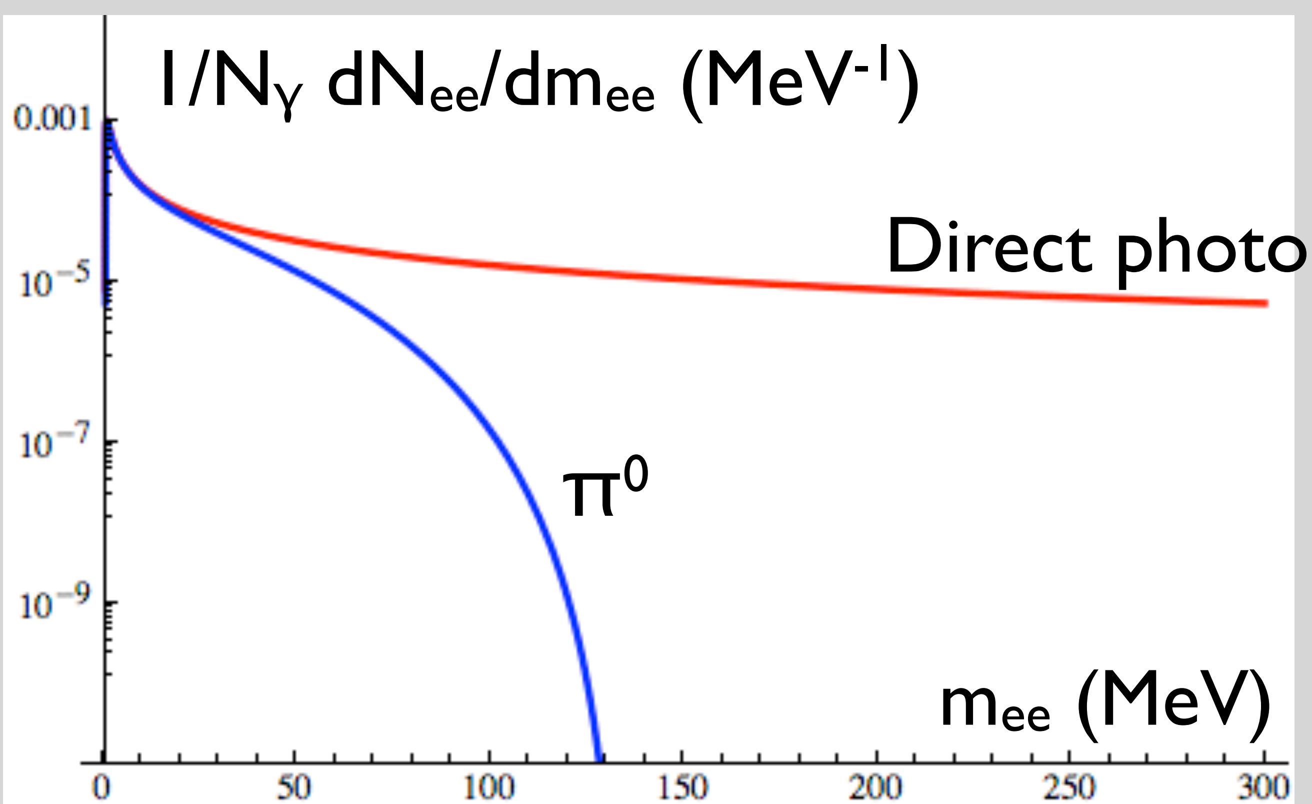
QED

phase space

Hadron decay: $S = |F(m_{ee}^2)|^2(1-\frac{m_{ee}^2}{M_h^2})^3$

form factor

Point-like process: $S \approx 1$ (for $p_T^{ee} \gg m_{ee}$)



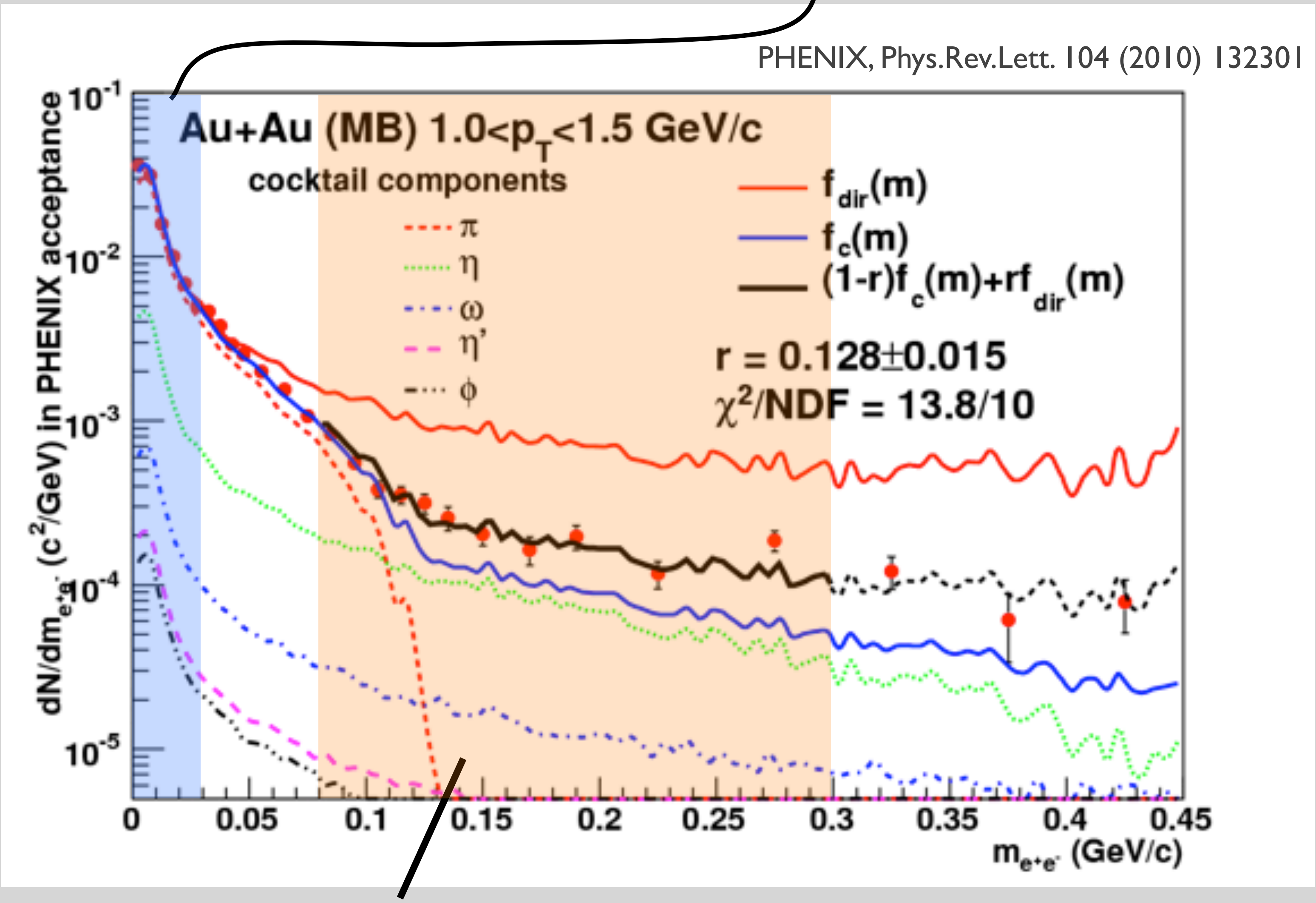
About 0.001 virtual photons with $m_{ee} > M_{pion}$ for every real photon

→ Avoid the π^0 background at the expense of a factor 1000 in statistics

Extraction of the Direct Photon Signal: Two-Component Fit

$$f(m_{ee}) = (1 - r) \cdot f_{cocktail}(m_{ee}) + r \cdot f_{direct}(m_{ee})$$

Separately normalized to data at m_{ee} < 30 MeV



Fit range: 80 < m_{ee} < 300 MeV

- Interpret deviation from hadronic cocktail (π, η, ω, η', φ) as signal from virtual direct photons
- Extract direct photon fraction r with two-component fit

$$r = \left. \frac{\gamma^*_{direct}}{\gamma^*_{inclusive}} \right|_{m_{ee} < 30\,\mathrm{MeV}}$$

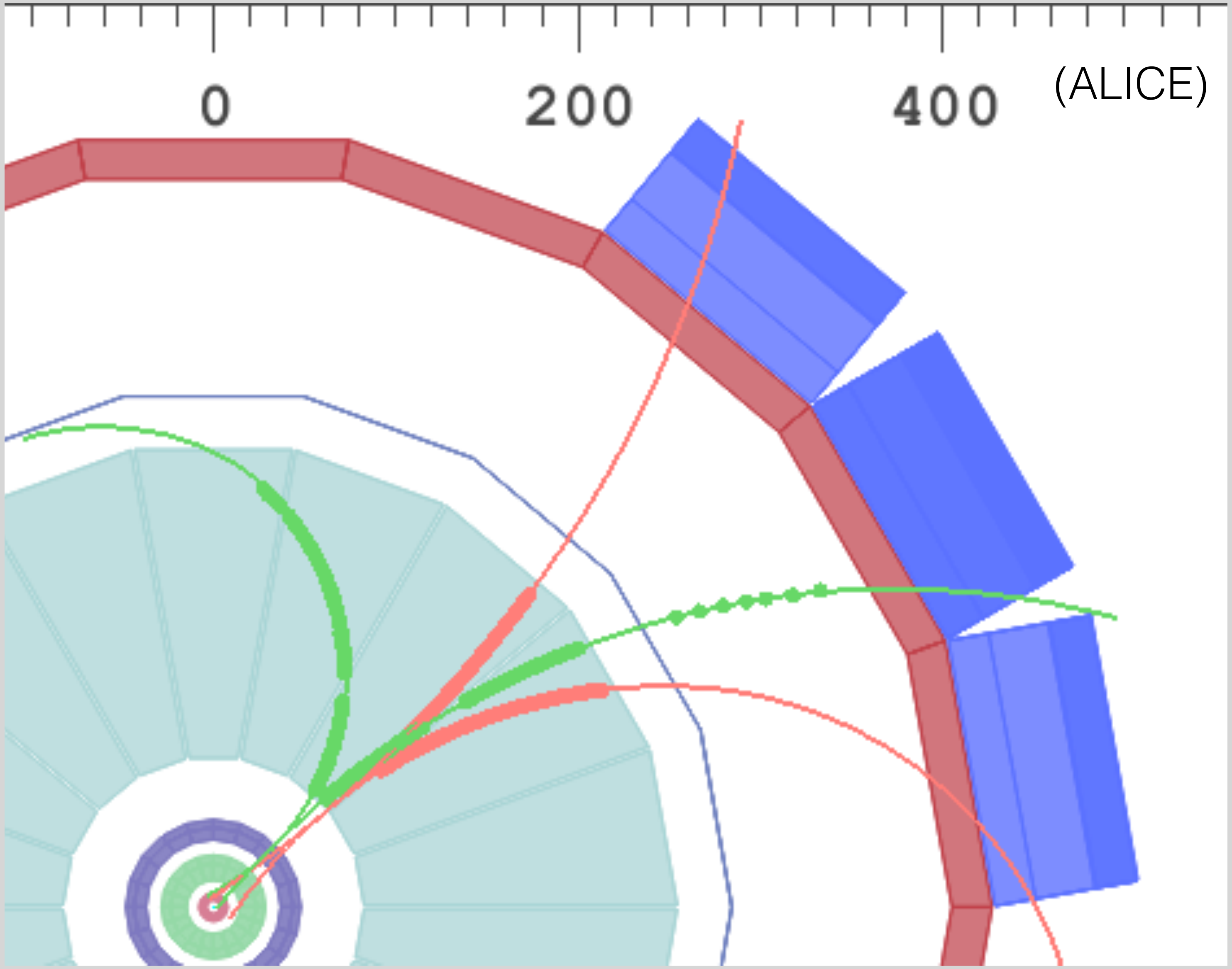
- Fit yields good χ2/NDF (13.8 / 10)

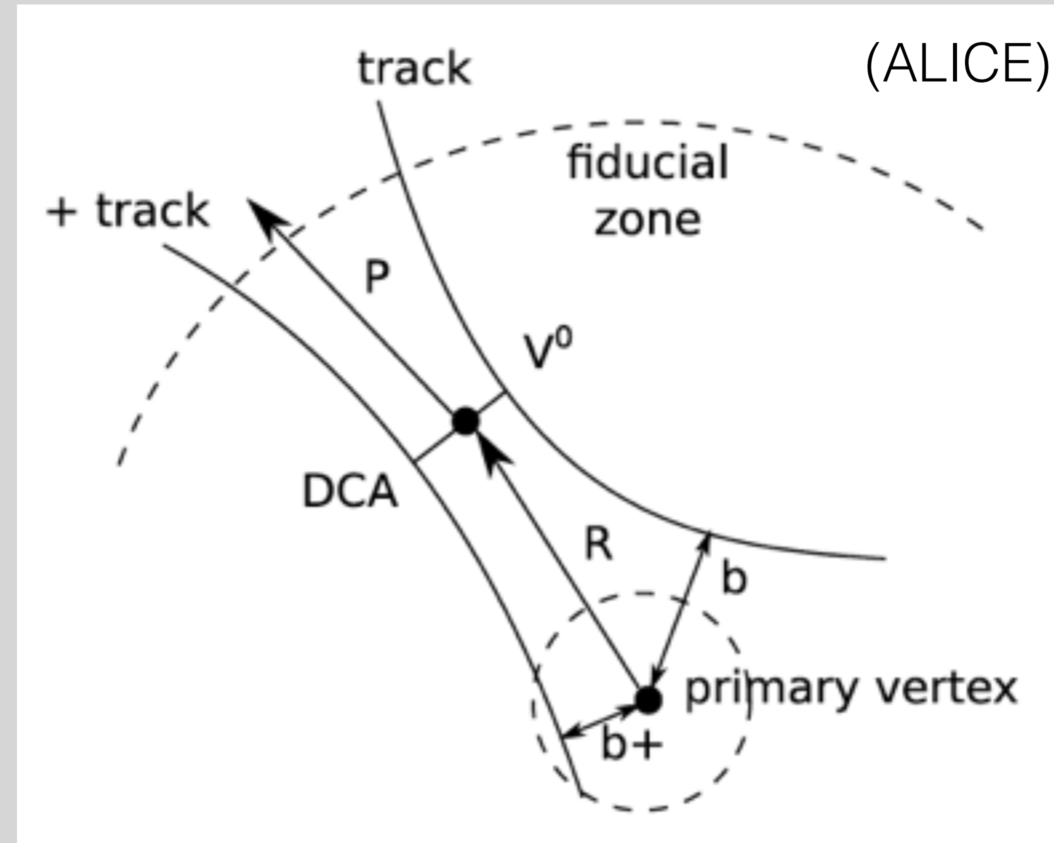
External Conversion

External Conversion: The Idea

- Use $\gamma \rightarrow e^+e^-$ conversion (pair production) and get photon properties (energy, momentum) from pair
- Use of tracking detectors for electron reconstruction allows better energy resolution
- Experiments use different methods for finding converted photons, depending on their detector capabilities
- ALICE: use displaced vertices
  - Tracking detectors find displaced vertex of e^+e^- pairs, pair is reconstructed as photon
- PHENIX: alternate track model
  - Look for e^+e^- pairs from conversion plane, then reconstruct photon properties for these pairs

ALICE: Measuring Photons via Conversions



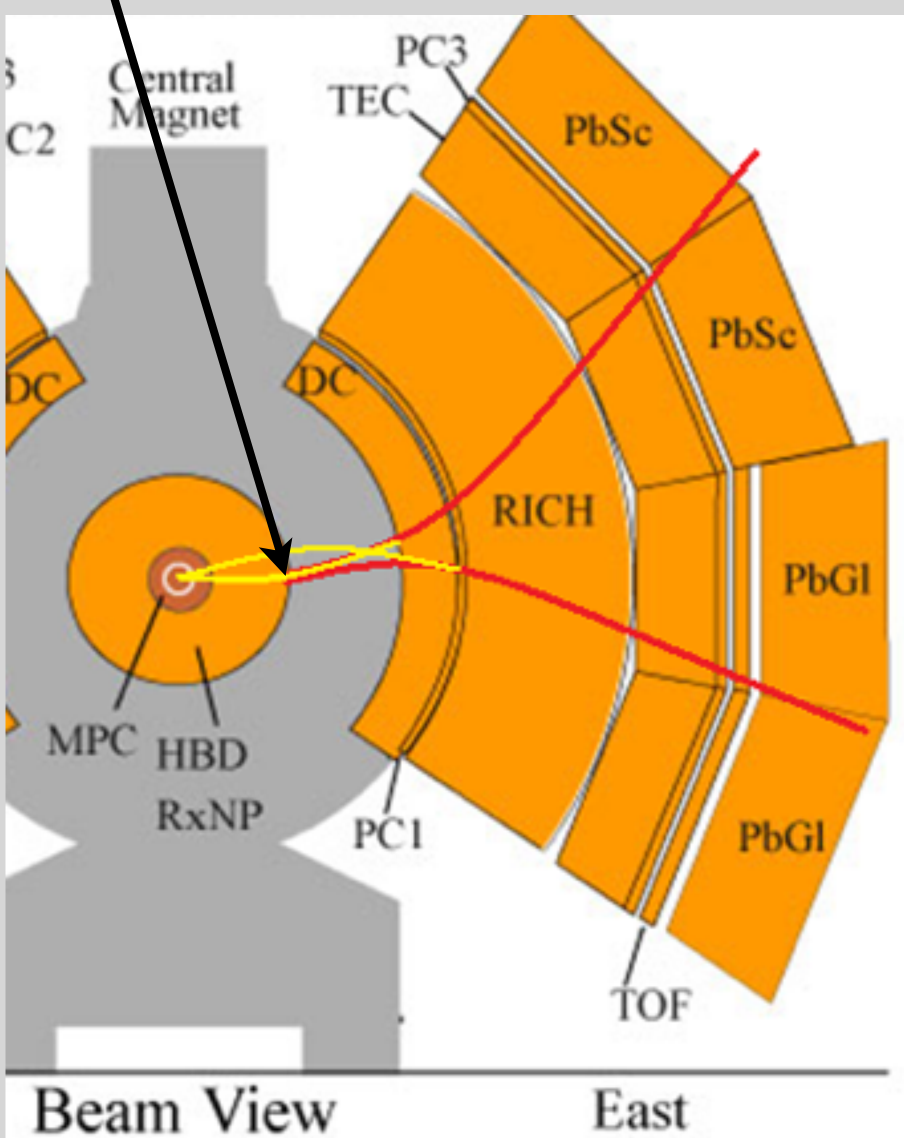


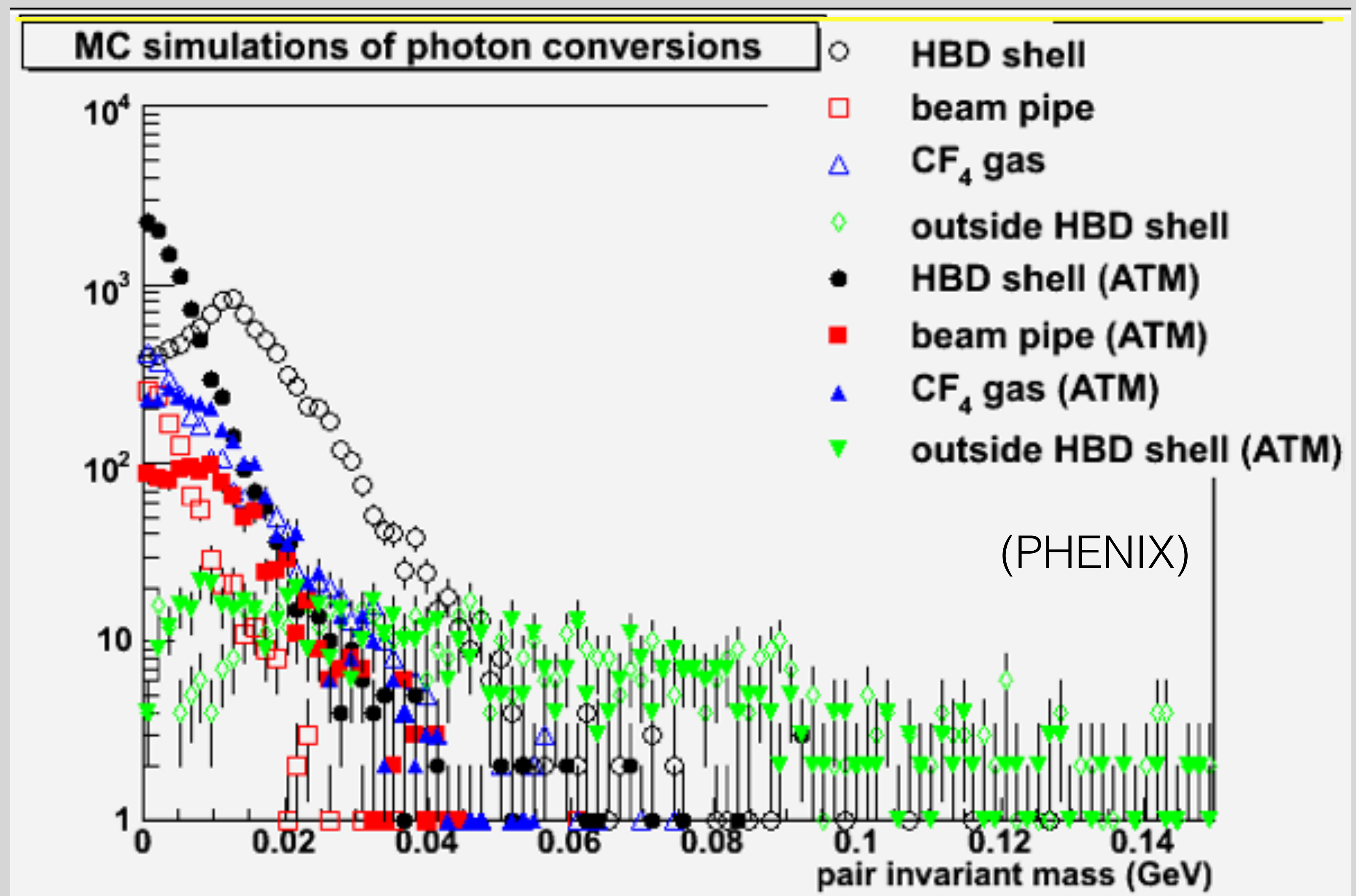
ALICE: photon conversion probability
~ 8% up to the middle of the TPC

Advantage of the conversion method:
Better resolution and higher purity of the photon sample at low p_T

PHENIX: The Alternate Track Model

- Photon conversions of interest originate from the HBD shell (r≈60cm)
  - Reconstruction assumes event vertex as origin
  - Can exploit this misreconstruction
  - Can correct for this with an alternate track model assumption





Direct Photons - A Short Introduction: Part II

Baldo Sahlmüller, IKF Uni Frankfurt

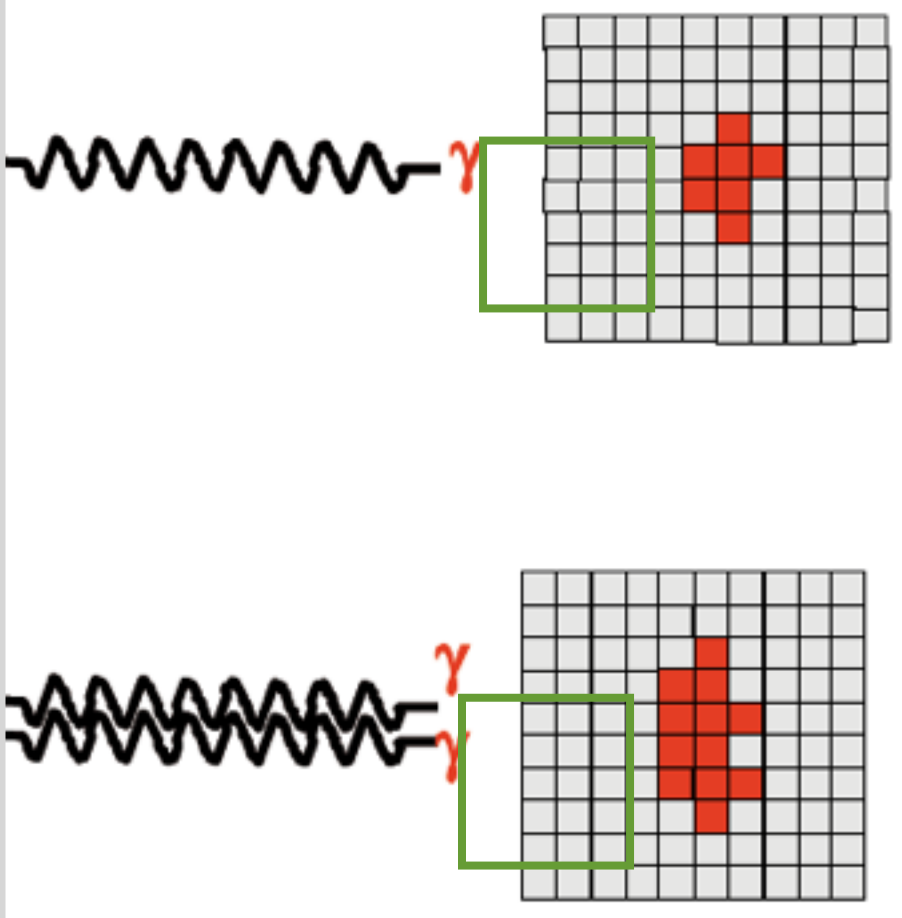
Lecture Week of the Helmholtz Research School
for Quark Matter Studies in Heavy Ion Collisions

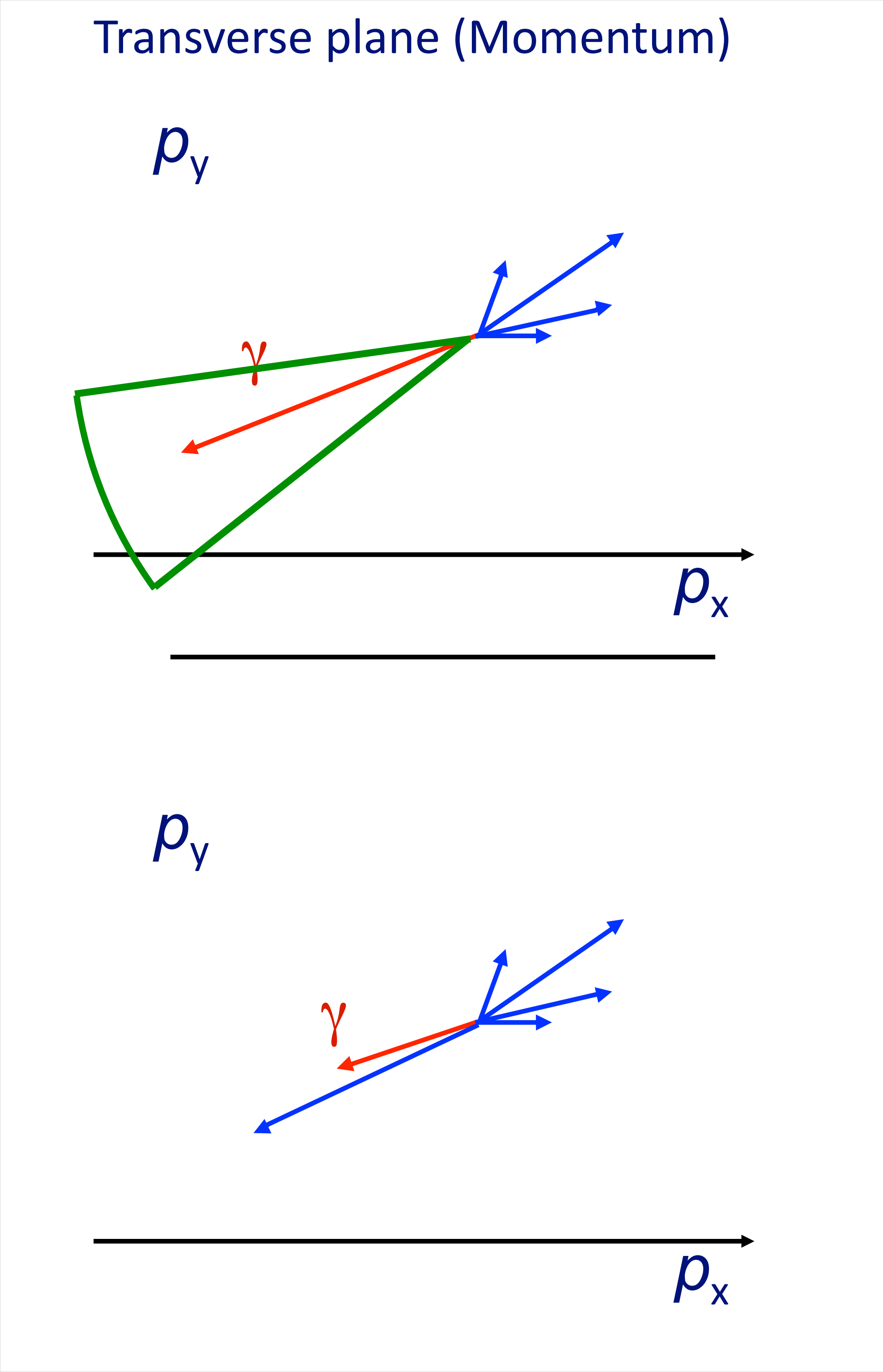
November 4-9, 2012, Burg Ebernburg, Germany

Results

Reminder I: Isolation Method

- Photons from hard scattering are "isolated", i.e. not surrounded by other particles
- To remove merging decay photons from high p_T π^0s, apply shower shape cuts



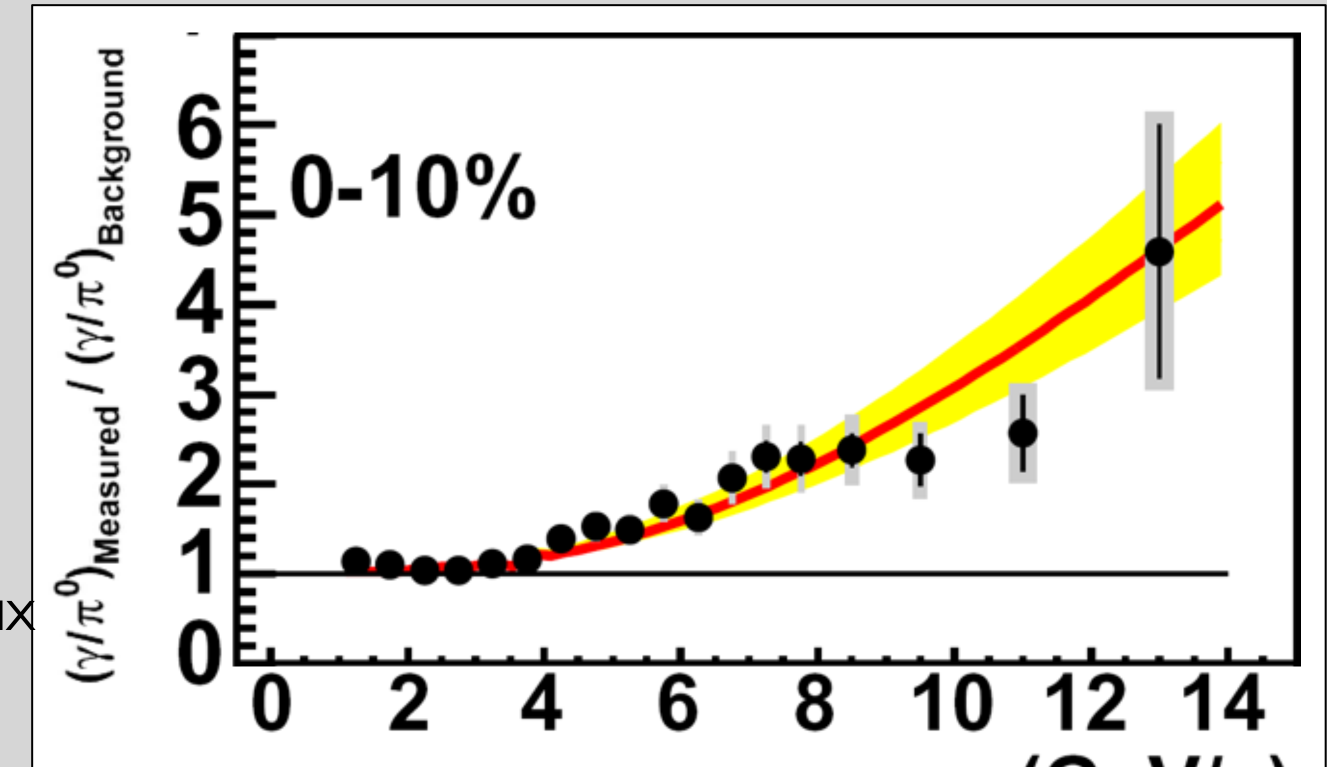


CMS Collaboration

Reminder 2: Statistical Subtraction

- Difficult (or impossible) to remove decay photons on an event-by-event basis, therefore do a statistical subtraction with all available data
- $\gamma_{direct} = \gamma_{inclusive} - \gamma_{decay}$
- For inclusive photons, remove contribution from hadrons and electrons, correct for detector effects
- Decay photons from simulation based on measured meson (π^0) spectra
- To minimize systematic uncertainties, use double ratio for subtraction, systematics between π^0 and inclusive γ measurement partly correlated

PHENIX



Phys.Rev.Lett.94:232301,2005

$$\gamma_{direct} = \gamma_{inclusive} - \gamma_{backgr} = (1 - \frac{\gamma_{backgr}/\pi^0}{\gamma_{inclusive}/\pi^0}) \cdot \gamma_{inclusive}$$

$$= (1 - 1/R) \cdot \gamma_{inclusive}$$

with $$R = \frac{\gamma_{inclusive}}{\gamma_{backgr}} = 1 + \frac{\gamma_{direct}}{\gamma_{backgr}} \equiv \frac{(\gamma_{inclusive}/\pi^0)_{meas}}{(\gamma_{backgr}/\pi^0)_{calc}}$$

Reminder 3: Internal Conversion

- Each source of real photons also emits virtual photons that decay into e^+e^- pair
- Invariant mass shape described by Kroll-Wada forumula
- Measured dielectron spectrum fit with function composed of cocktail and direct photon shape (from Kroll-Wada)
- Fraction of direct photons and inclusive photons from fit:

$$r = \left.\frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}}\right|_{m_{ee}<30\text{ MeV}}$$

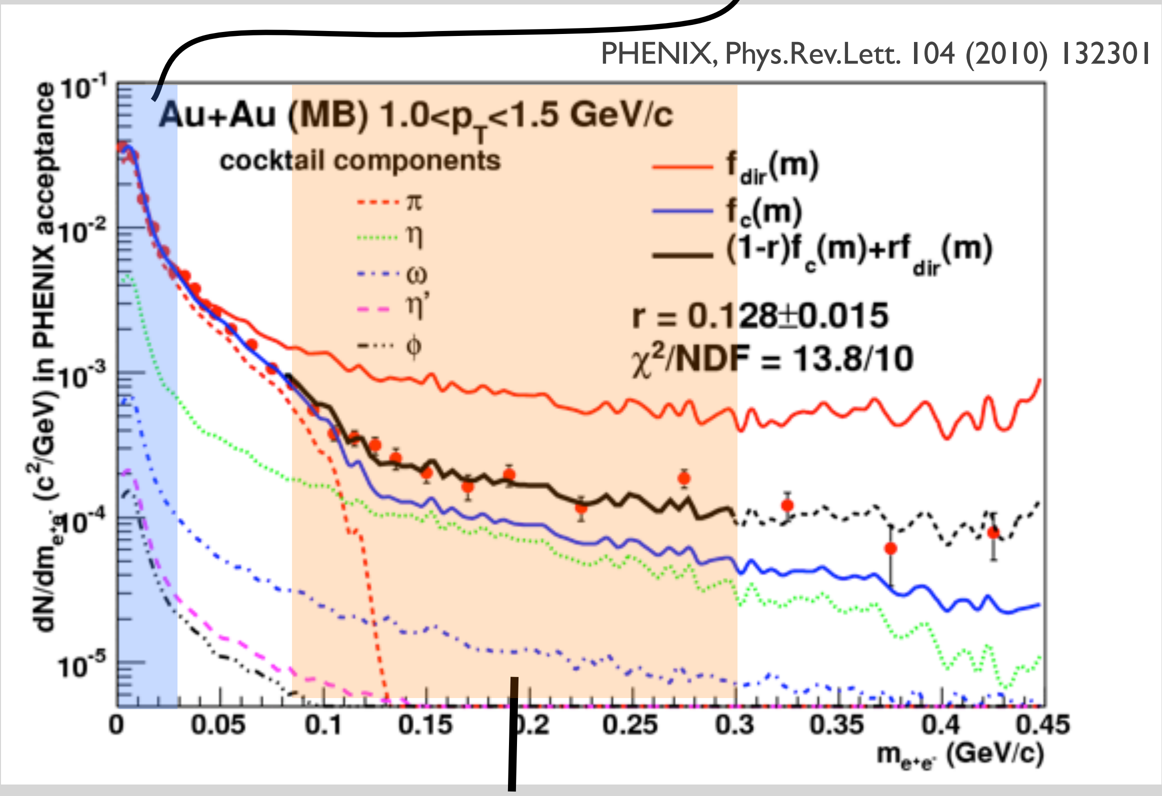
Kroll-Wada-Formula

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

invariant mass of Dalitz pair — QED — phase space — form factor

$$f(m_{ee}) = (1-r)\cdot f_{\text{cocktail}}(m_{ee}) + r\cdot f_{\text{direct}}(m_{ee})$$

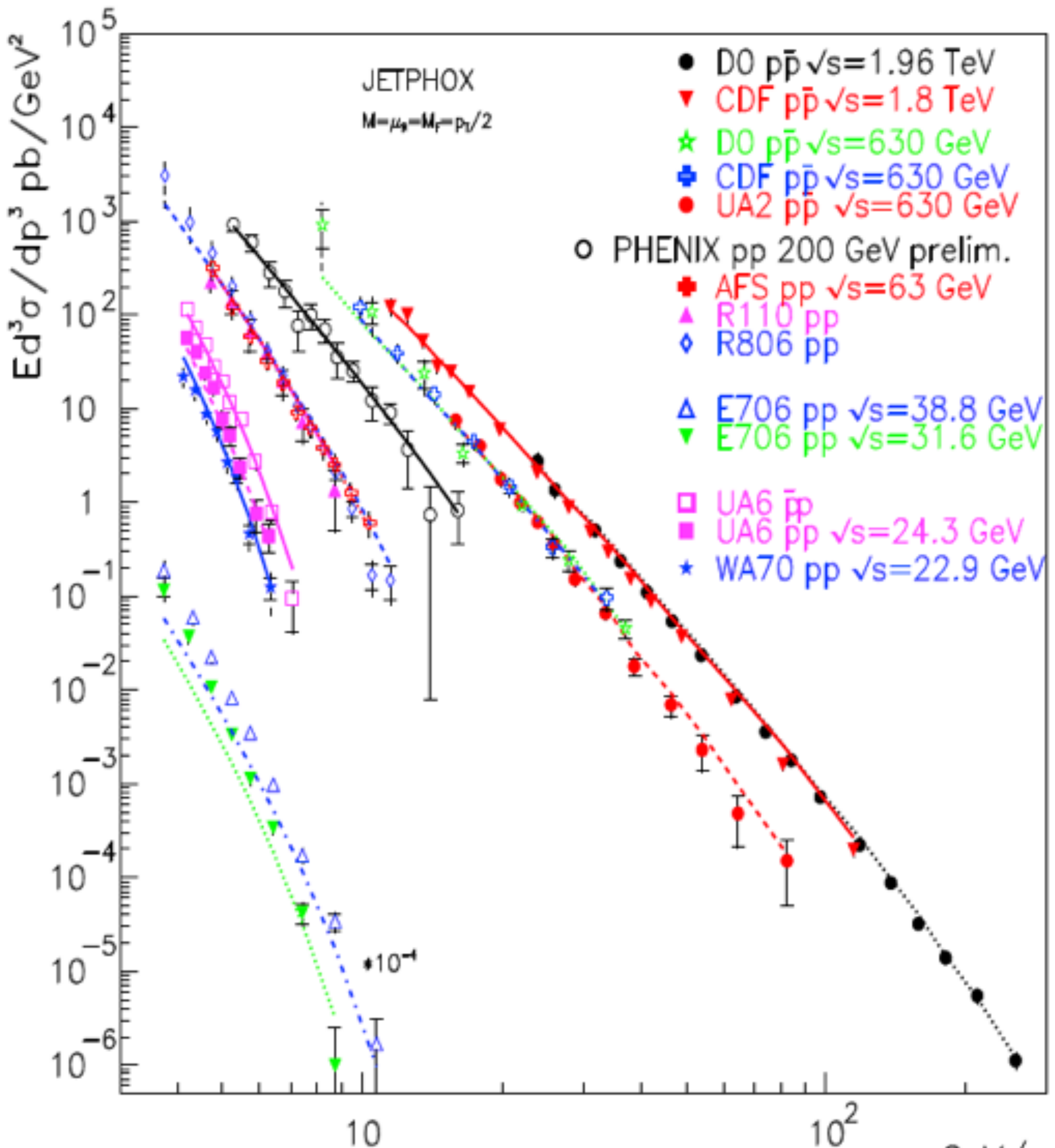
Separately normalized to data at m_{ee} < 30 MeV



Fit range: 80 < m_{ee} < 300 MeV

p+p Collisions

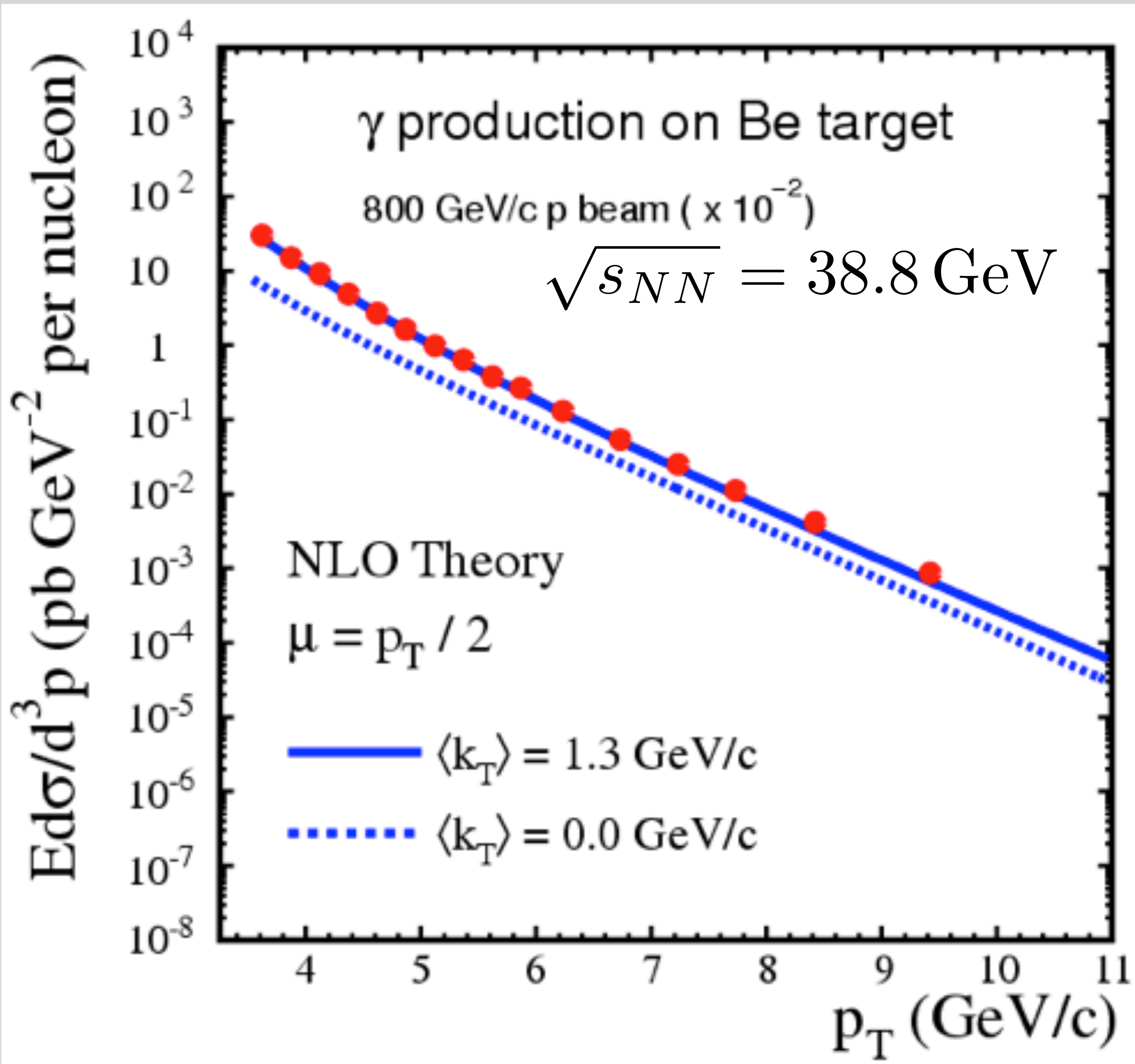
p+p(p bar) Direct Photon Data and pQCD – Status as of ~ 2006 (I)



Aurenche et al., Phys.Rev. D73 (2006) 094007

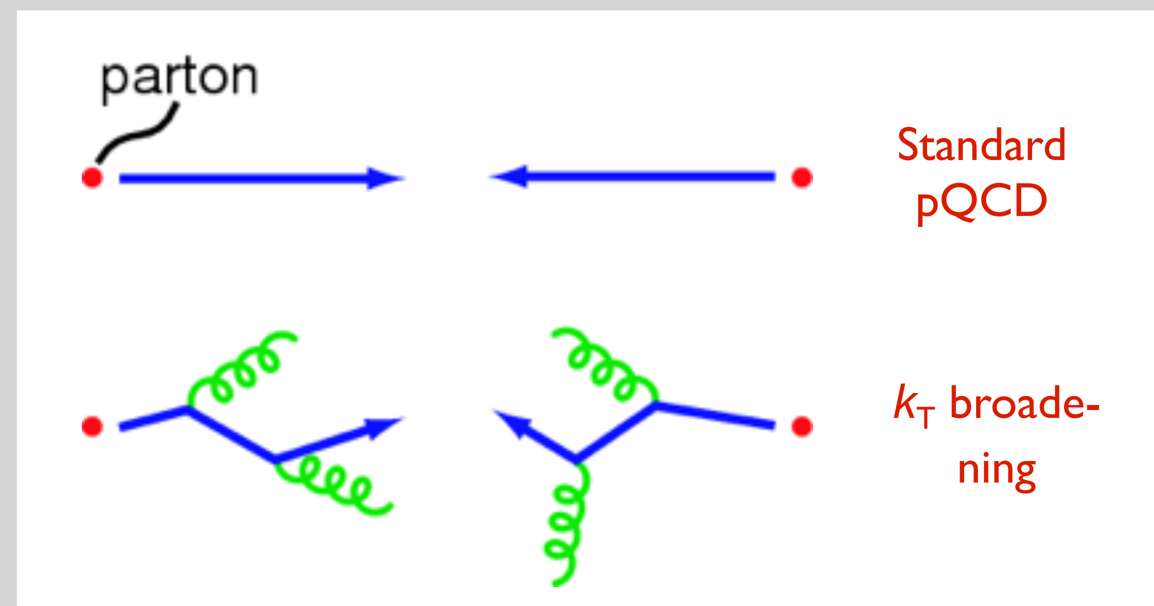
- Decent agreement at large √s
- Substantial deviations between data and NLO pQCD at small √s
- Questions:
  - Is there a systematic pattern of deviation?
  - If so, can the introduction of additional transverse momentum (k_T) of initial partons improve the agreement?
  - Are the data sets mutually consistent?

Is k_T Broadening Needed to Describe Direct Photon Data?



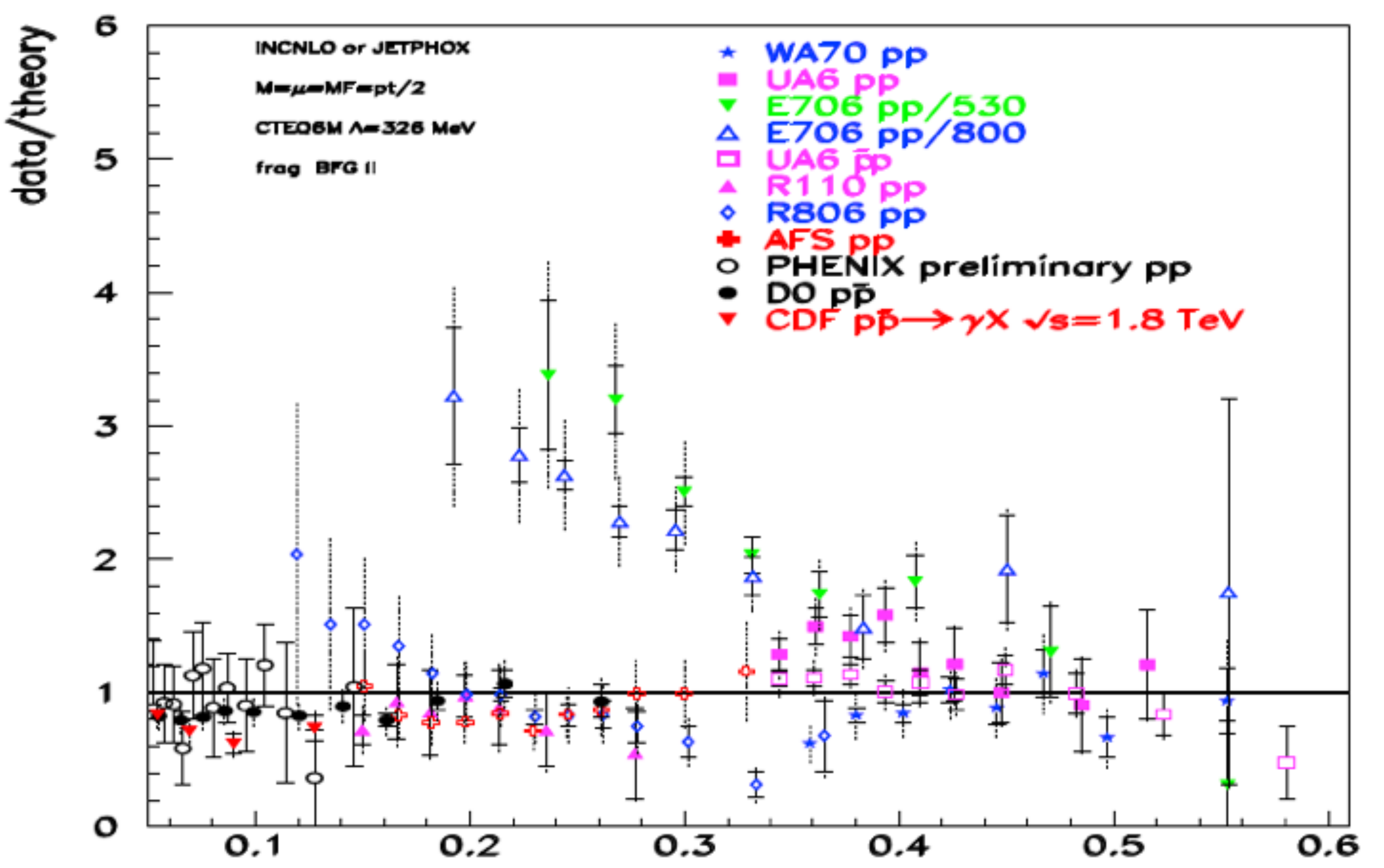
E706, Phys.Rev.D70:092009,2004

- Data from E706 fixed target experiment can be explained with $\langle k_T \rangle \approx 1.3$ GeV/*c*



Is there evidence for k_T broadening in p+p at larger √s ?

p+p(p bar) Direct Photon Data and pQCD – Status as of ~ 2006 (II)



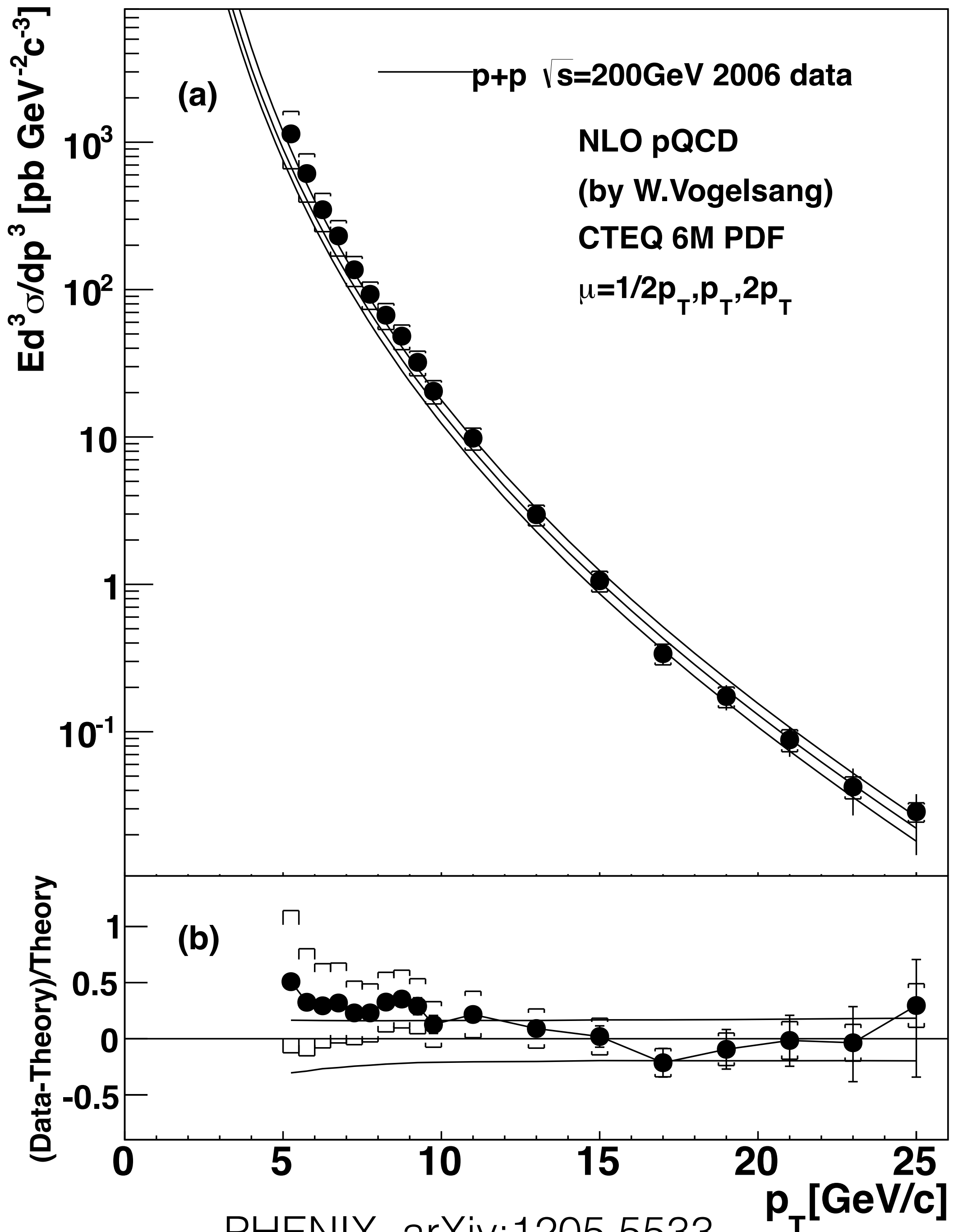
Aurenche et al., Phys.Rev. D73 (2006) 094007

$x_T = 2p_T/\sqrt{s}$

Only E706 data show strong deviation from NLO QCD.
Probably need new data at low $\sqrt{s}$ to settle the issue.

Direct Photons in p+p at 200 GeV

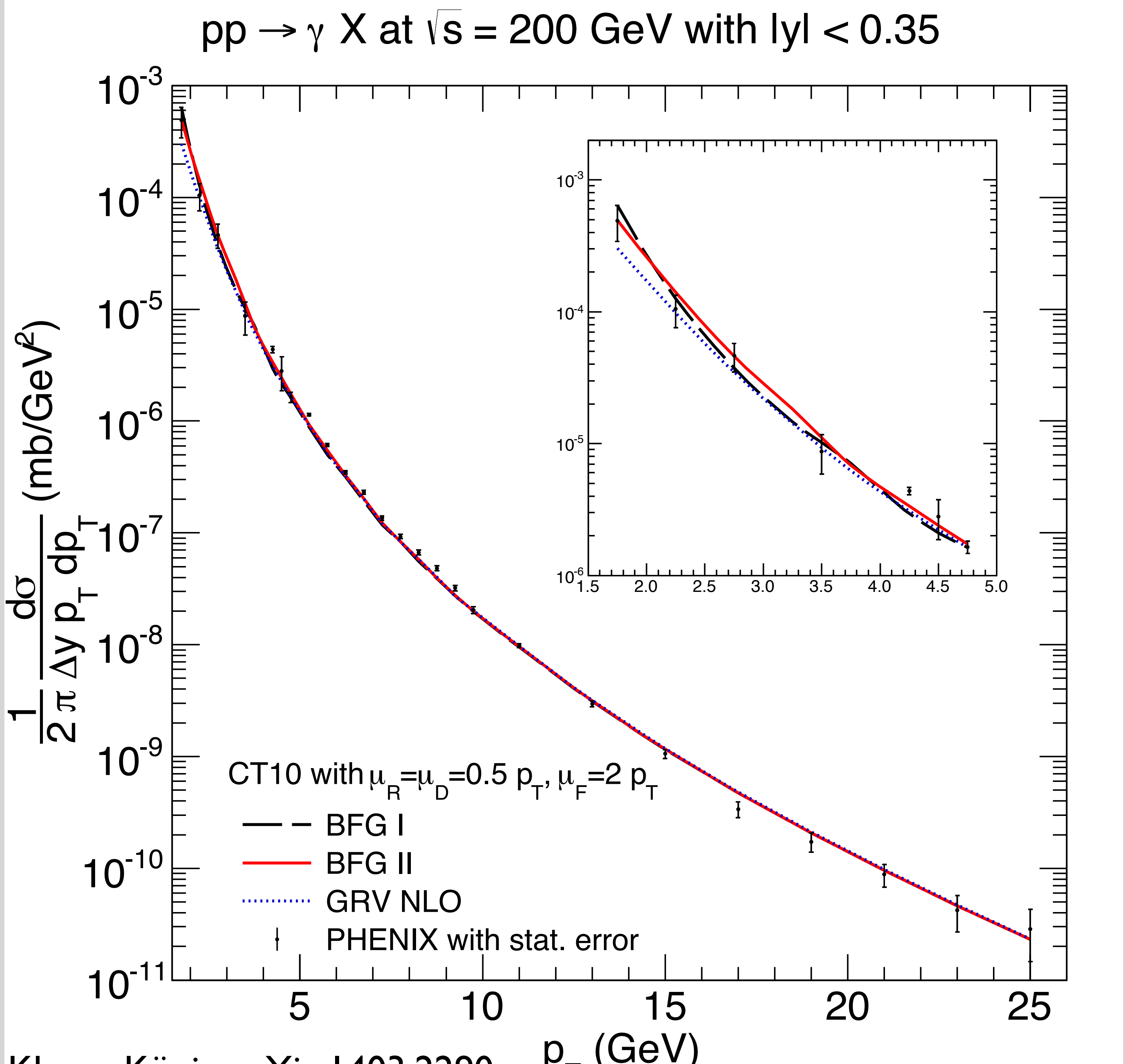
- Analysis includes a TOF cut to remove contamination from cosmics at very high p_T
- Data compared to pQCD calculation at three different scales
- Good agreement between theory and data over whole p_T range
- pQCD dominated by directly produced photons (in contrast to fragmentation photons) at high p_T



PHENIX, arXiv:1205.5533

A more detailed look

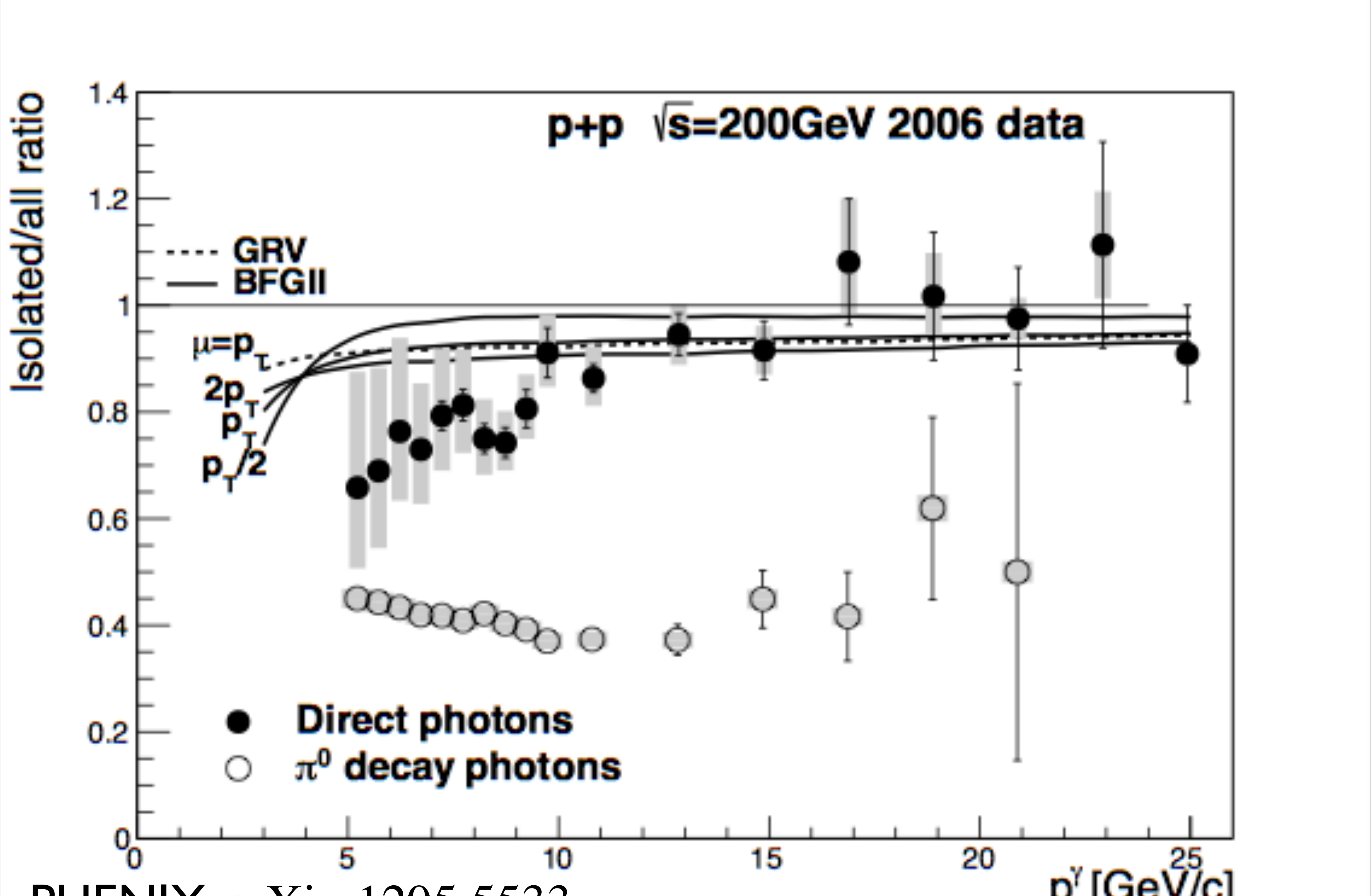
- Higher precision PHENIX data at low p_T available
  - using internal conversion method
- pQCD calculations depend on fragmentation component
  - Data can further constrain fragmentation functions
- χ^2 test of available FF against data
  - high p_T part as control region
- Data favor BFG II FF



Klasen König: arXiv:1403.2290

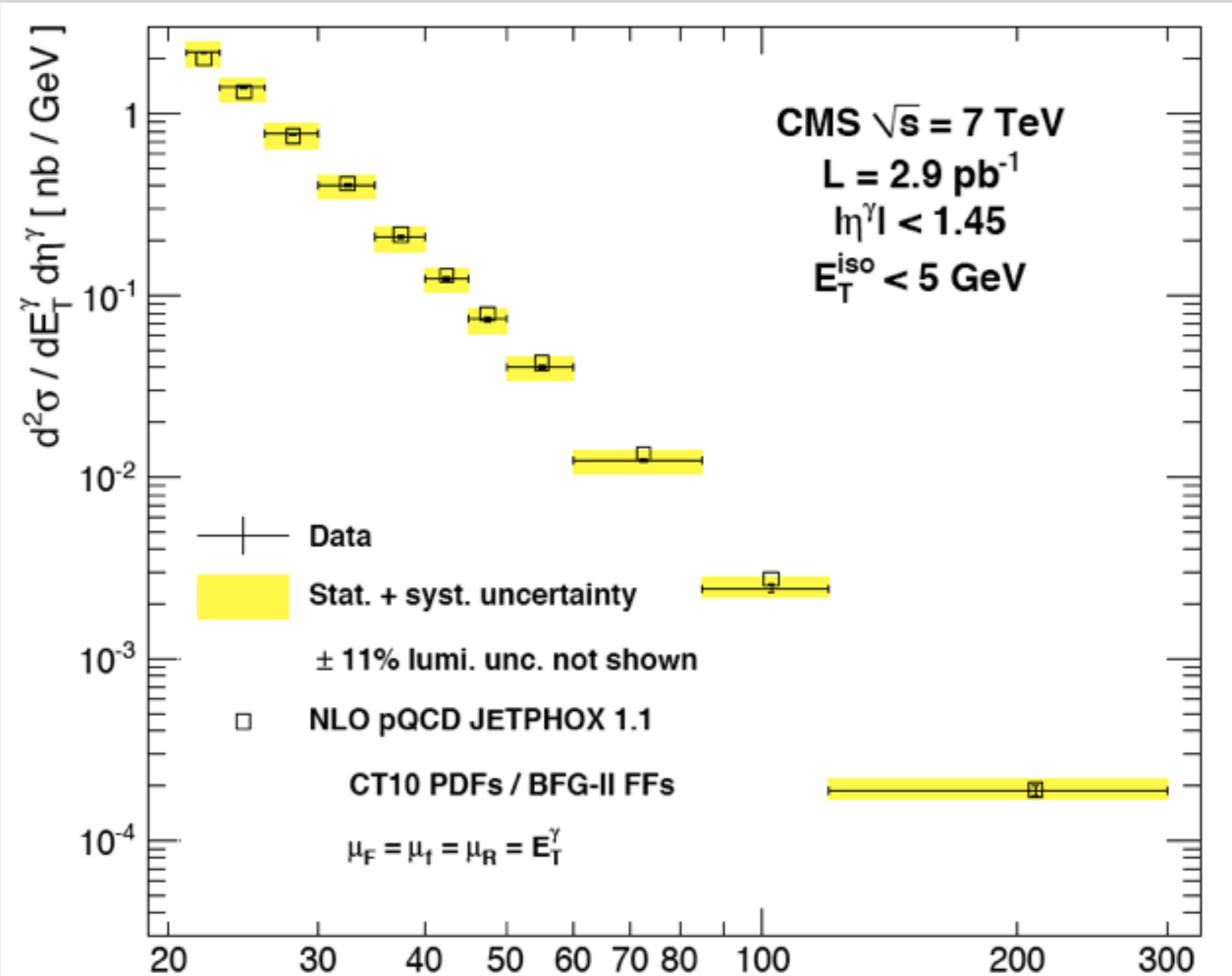
Adding an Isolation Criterium

- Applying isolation cut to photon candidates: most photons are isolated (~90% at high p_T)
- Theoretical calculations agree with the data, low p_T photons have larger fragmentation component



PHENIX, arXiv:1205.5533

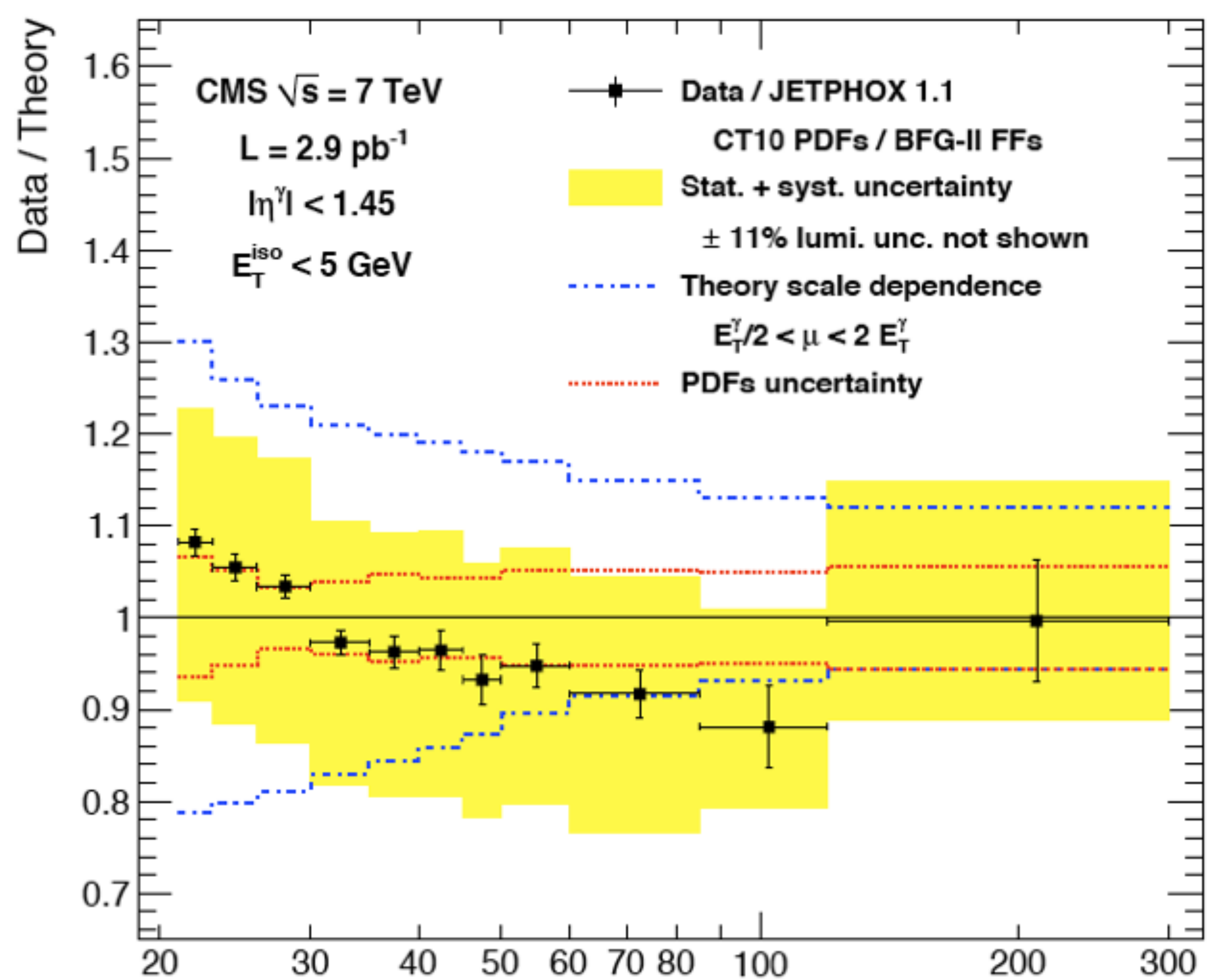
Isolated Photon Spectrum in p+p at 7 TeV (CMS)



CMS, Phys.Rev.Lett. 106 (2011) 082001

- The photon reconstruction and selection efficiencies are determined from PYTHIA:
  $\varepsilon = 0.916 \pm 0.034$
  (rather independent of photon energy)
- Spectrum corrected for finite energy resolution

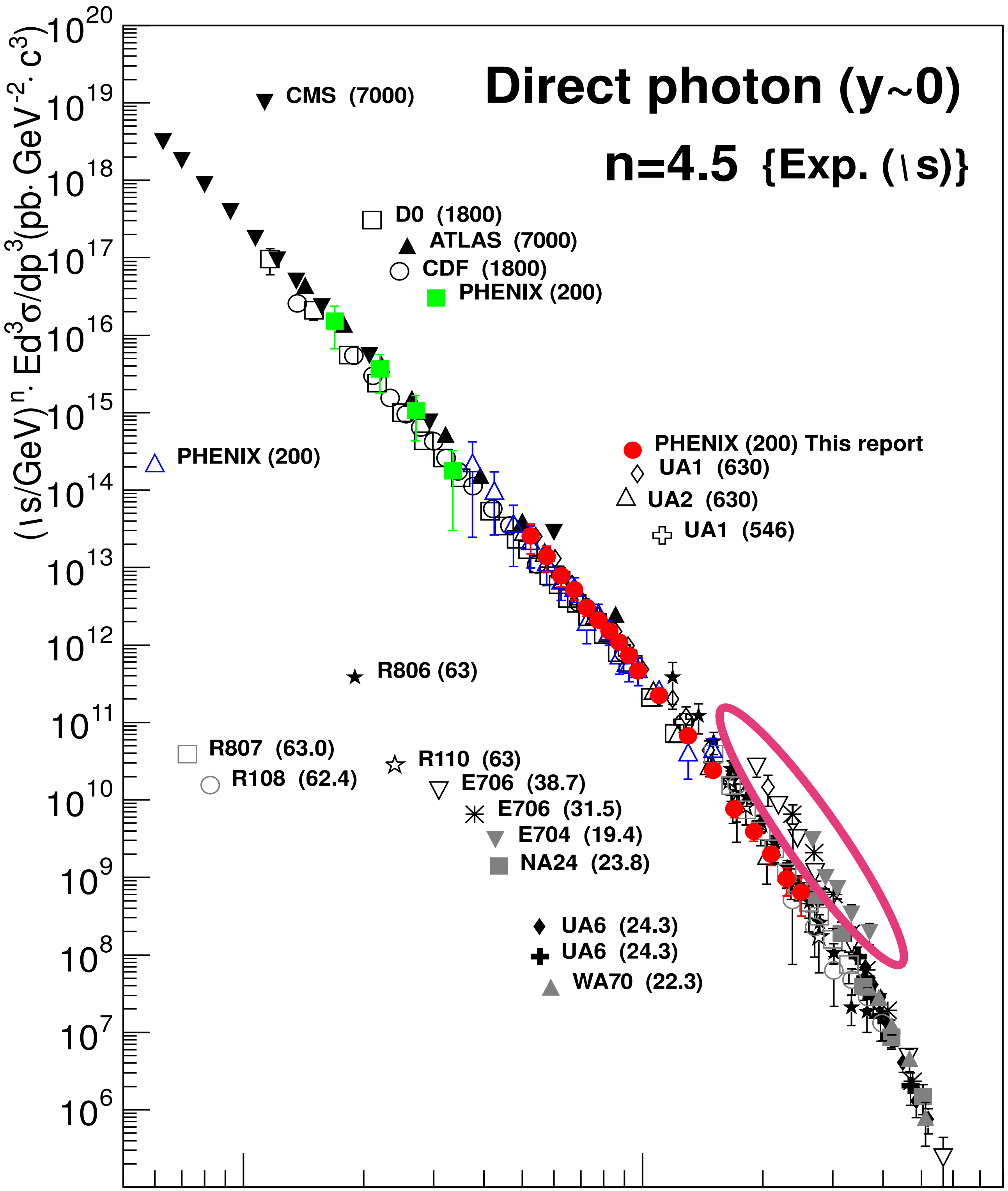
Isolated Photons in p+p at 7 TeV: Agreement with NLO pQCD



CMS, Phys.Rev.Lett. 106 (2011) 082001

P. Aurenche et al., Eur. Phys. J. C 13 (2000) 347 (http://lapth.in2p3.fr/PHOX_FAMILY).

A New "Complete" Picture

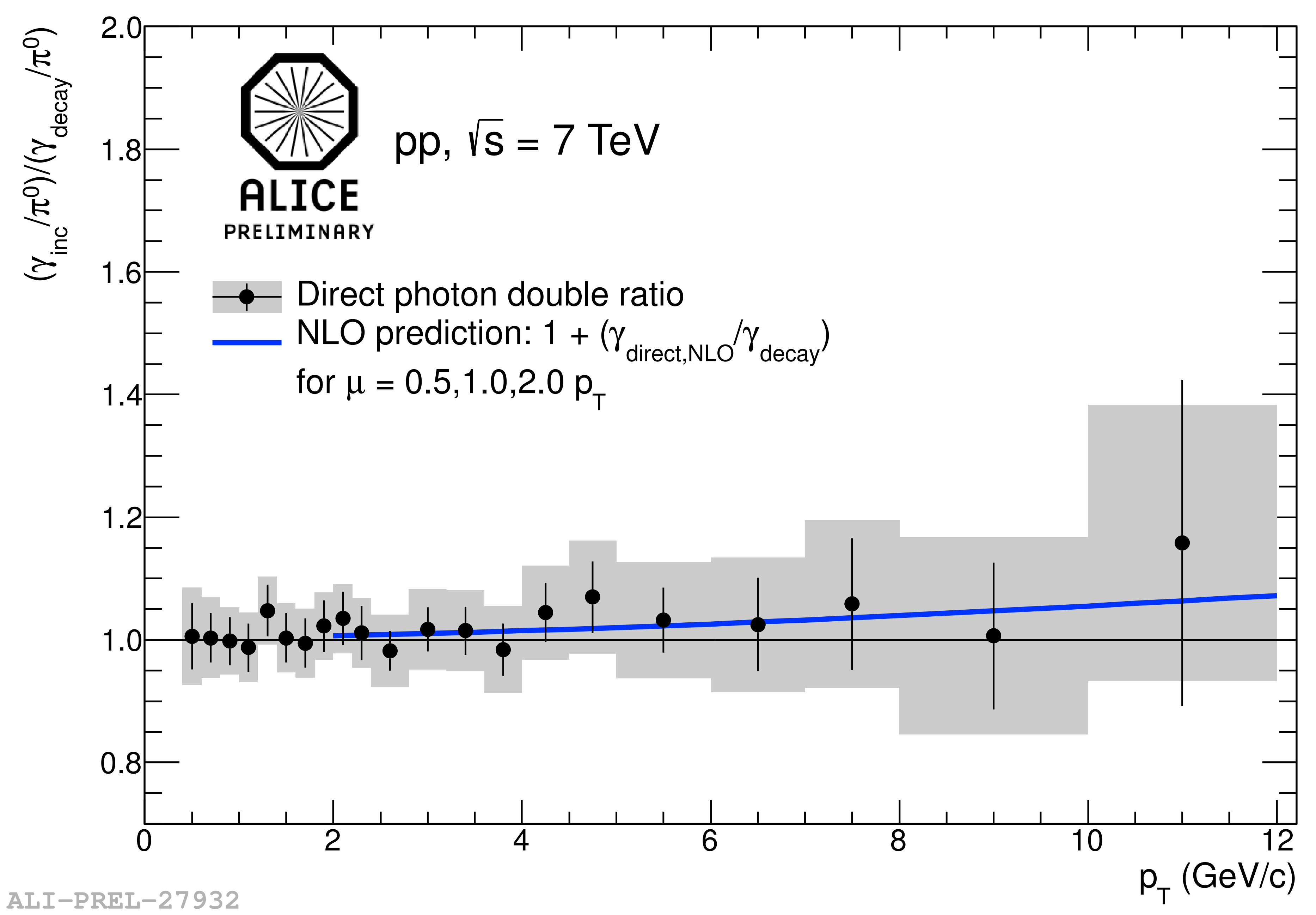


PHENIX, 10^{-2} arXiv:1205.5533 10^{-1} x_T ← $x_T = 2p_T/\sqrt{s}$

- *p*+*p* (*p* bar) plotted vs. x_T
- Data scaled with empirical $(\sqrt{s})^n$ with n=4.5
- Pure vector gluon exchange: n=4 as in Rutherford scattering
- However, scale breaking effects in QCD, they empirically taken into account for by assuming n-4 = 0.5
- All data are on one universal curve

➡QCD works

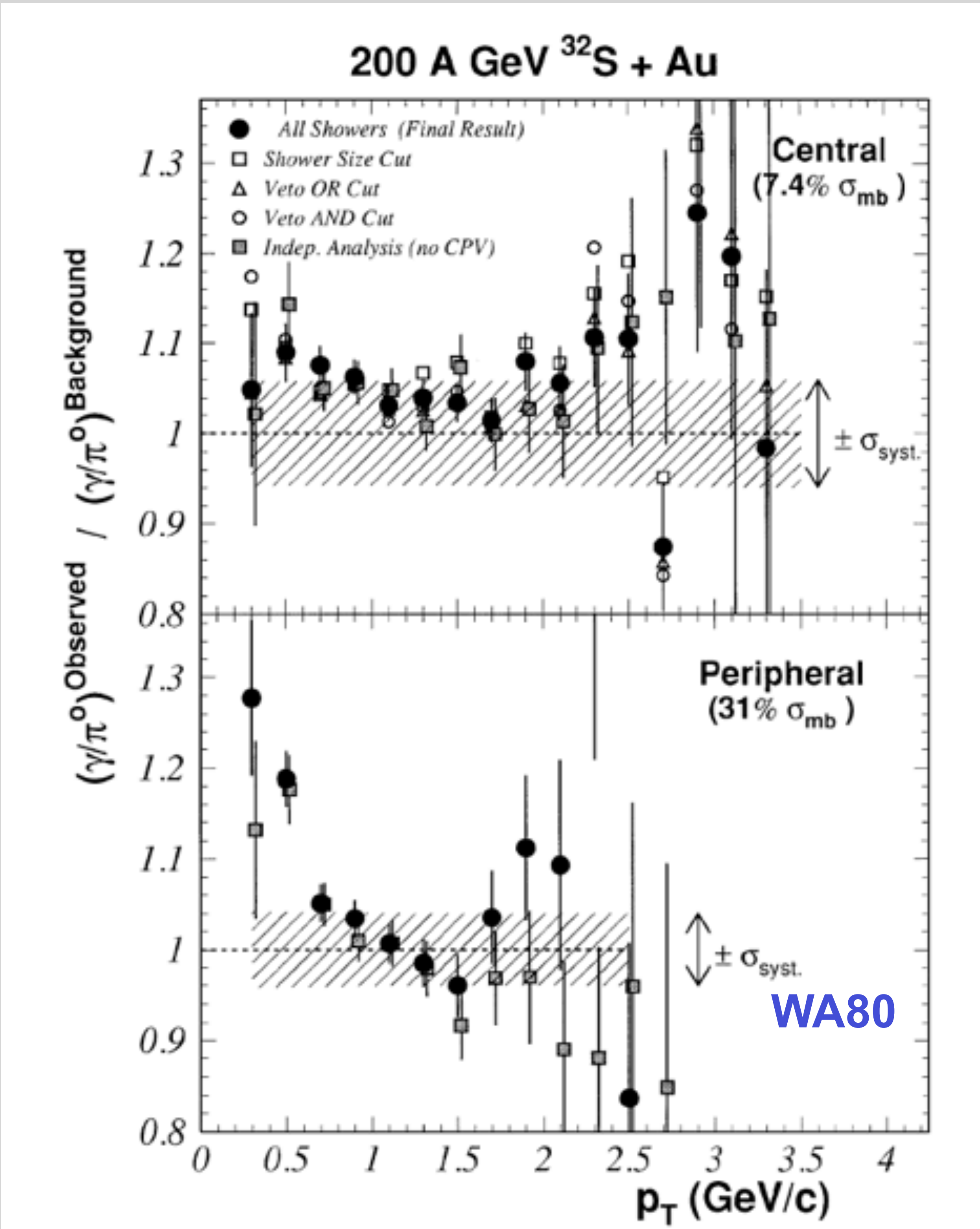
Direct Photon Search in p+p at LHC at Low p_T: Is It Possible?



Possible signal much smaller than systematic errors

Results in A+A

Early CERN SPS Results: Upper Limits



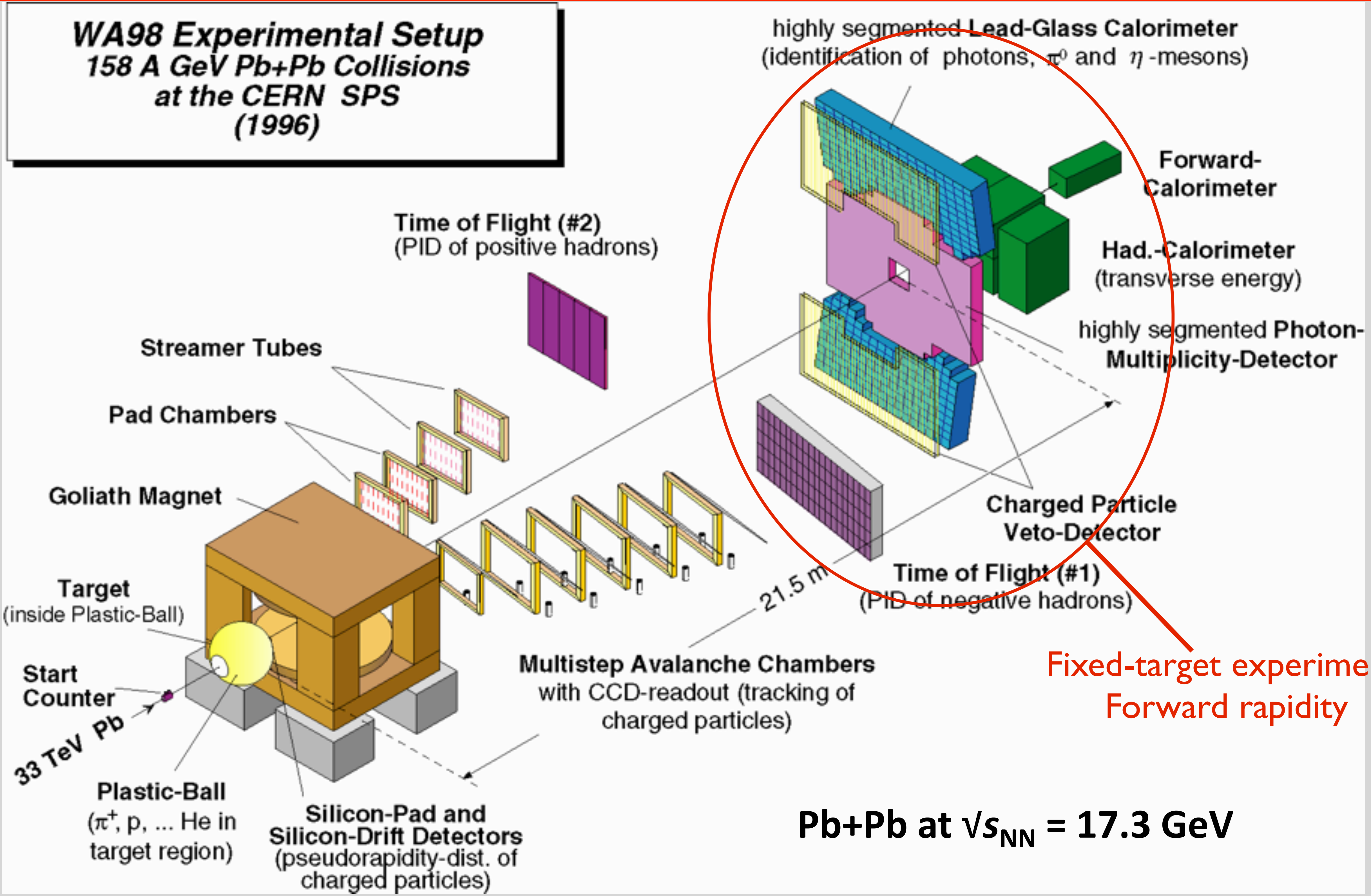
on γ_{direct} / $\gamma_{background}$

Experiment	*p*	System	Upper limit
HELIOS 2	0.1 – 1.5	p-W, O-W, S-W	13%
WA80	0.4 – 2.8	O-Au	15%
CERES	0.4 – 2.0	S-Au	14%
WA80	0.5 – 2.5	S-Au	12.5%

1. Z.Phys.C46:369-376,1990
2. Z.Phys.C51:1-10,1991
3. Z.Phys.C71:571-578,1996
4. Phys.Rev.Lett.76:3506-3509,1996

Early fixed target experiments at the CERN SPS only gave upper limits

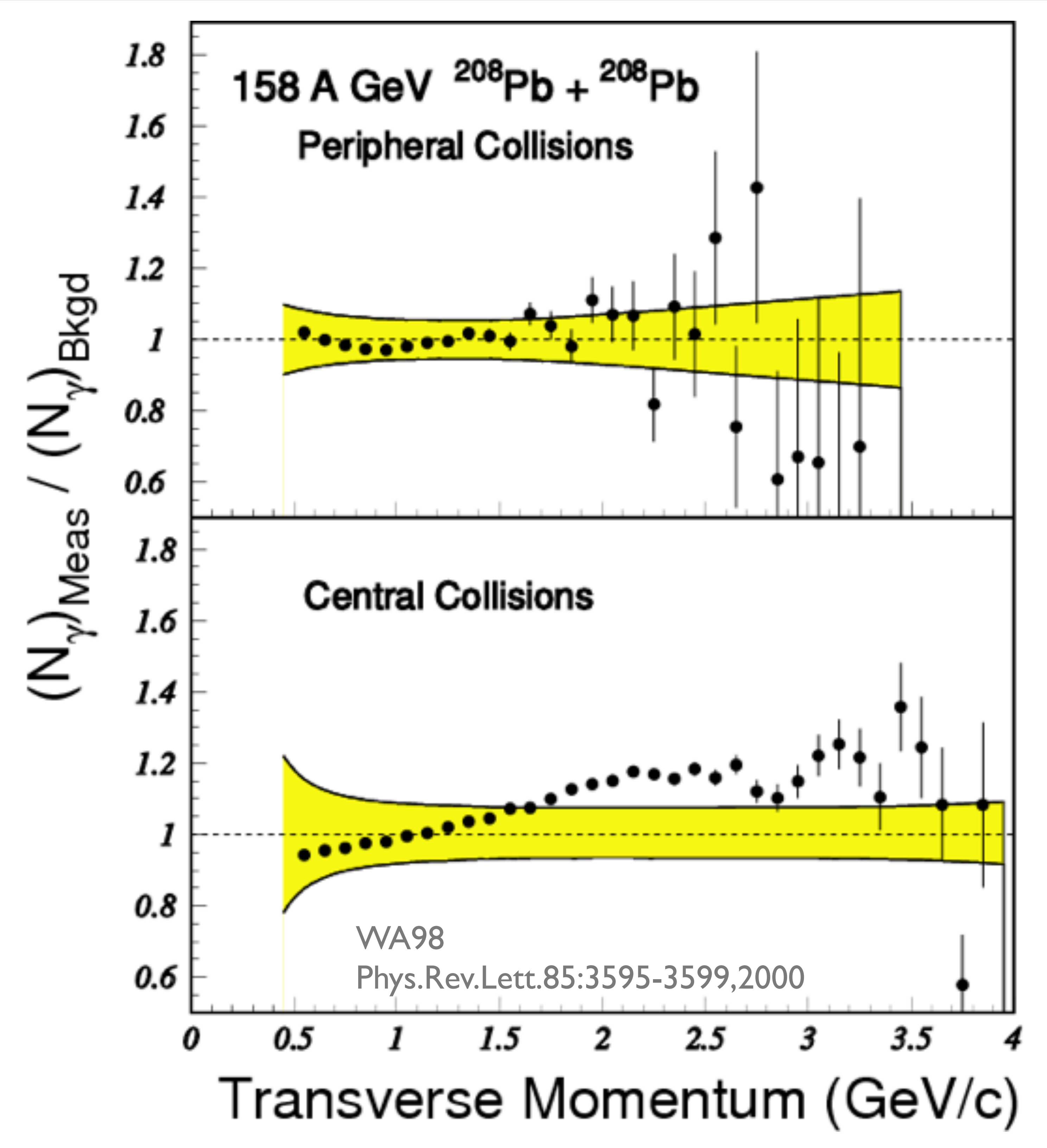
Photons as SPS: WA98 Experiment



Fixed-target experiment:
Forward rapidity

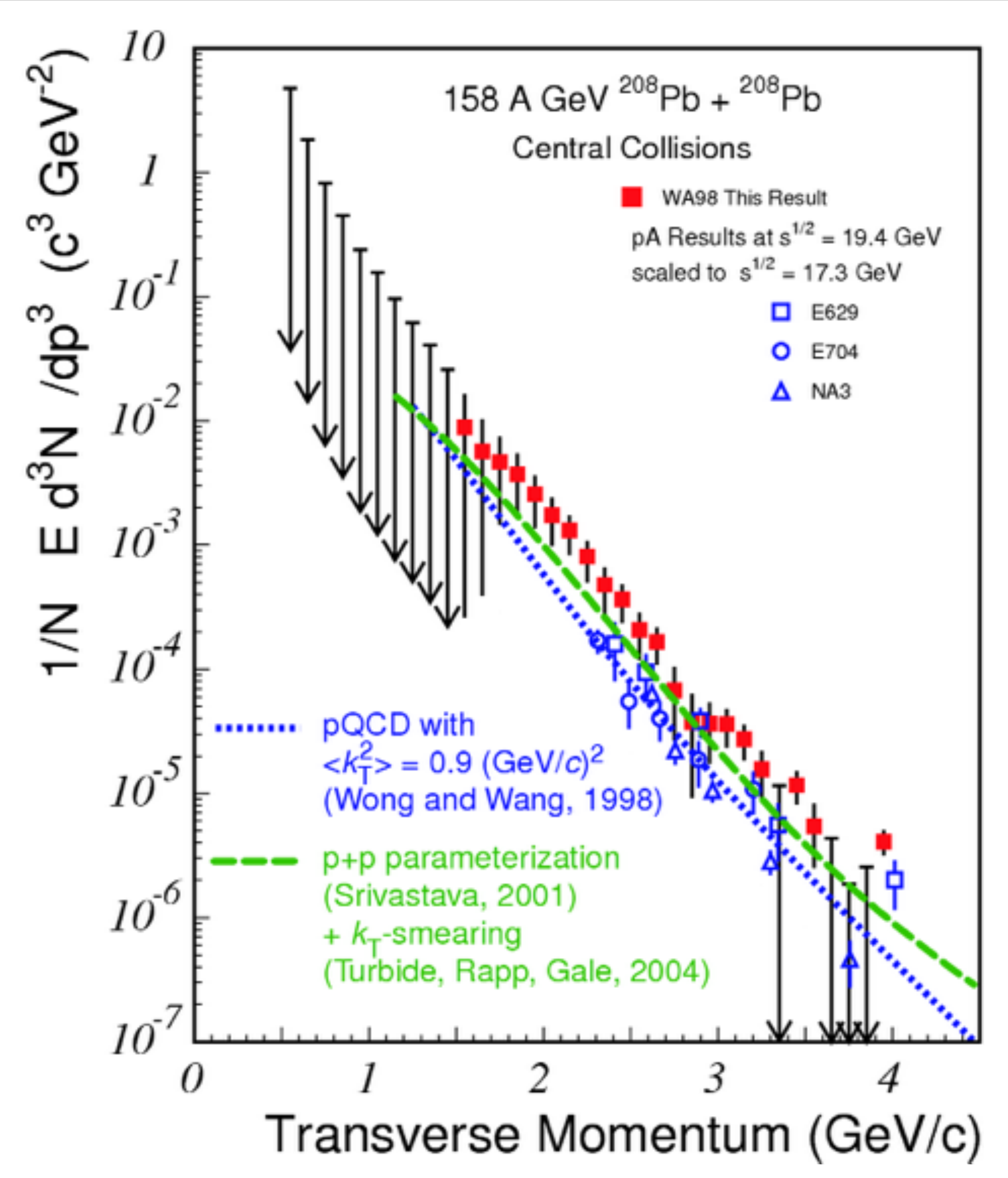
Pb+Pb at $\sqrt{s_{NN}}$ = 17.3 GeV

WA98 Result on Direct Photons



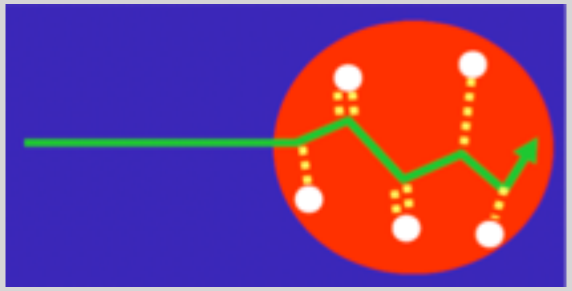
- No signal within errors in peripheral collisions
- 20% direct photon excess at high pT in central Pb+Pb collisions at CERN SPS

WA98 Direct Photon Spectrum: Hard Scattering + Nuclear k_T Broadening ?

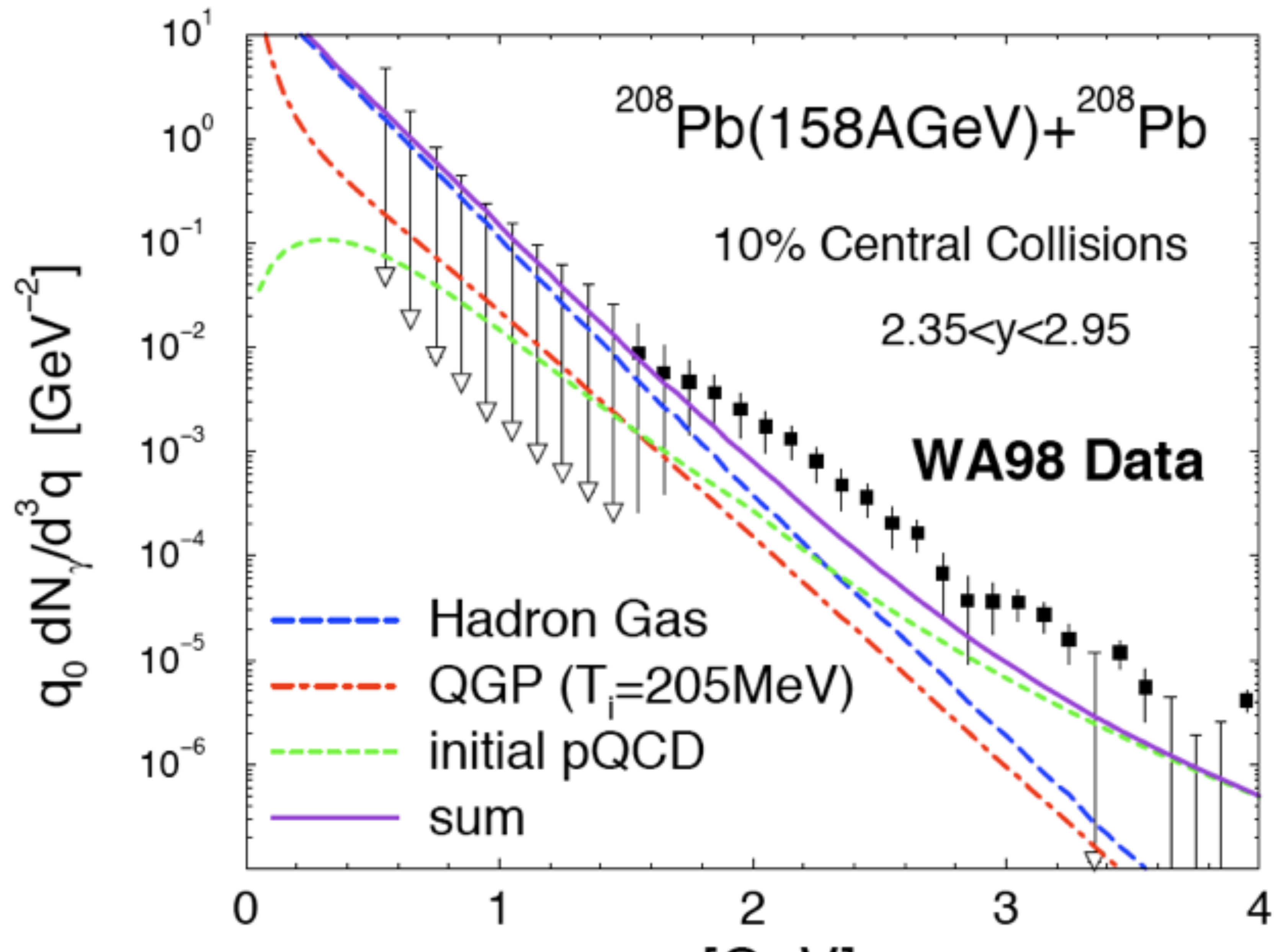


- Better p+p and p+A measurement desirable
- Very unlikely that Pb+Pb spectrum is just hard scattering

Cronin-effect:
Multiple soft scattering in p+A prior to hard scattering ("nuclear k_T")



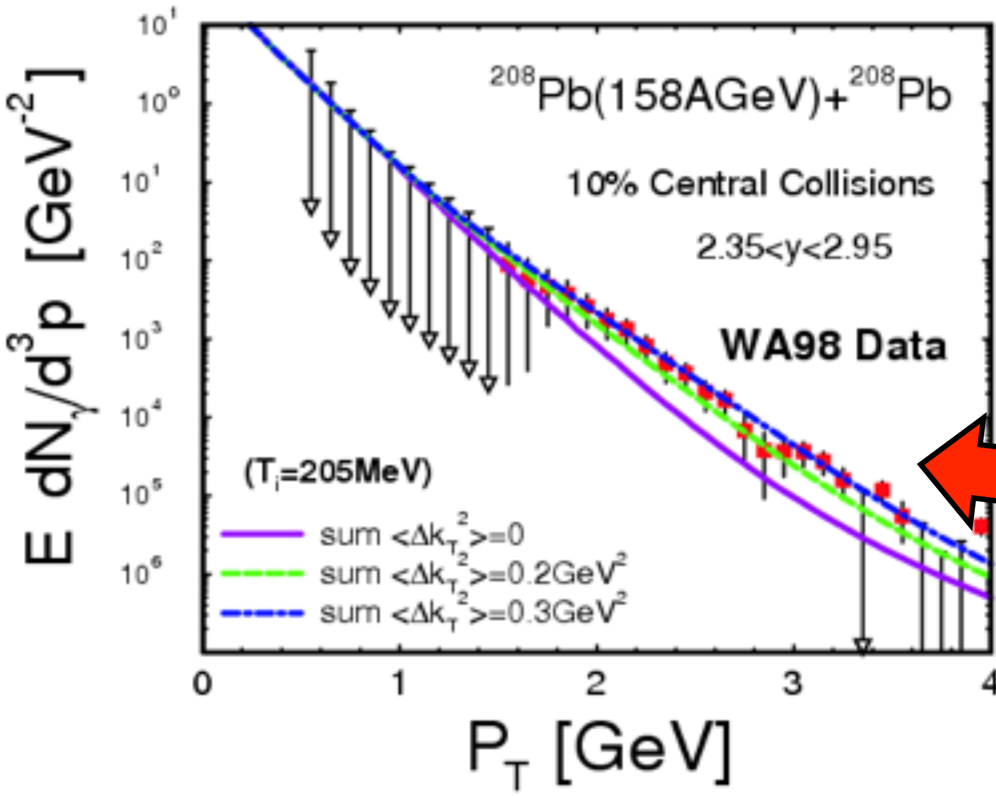
Interpretation of the WA98 Data



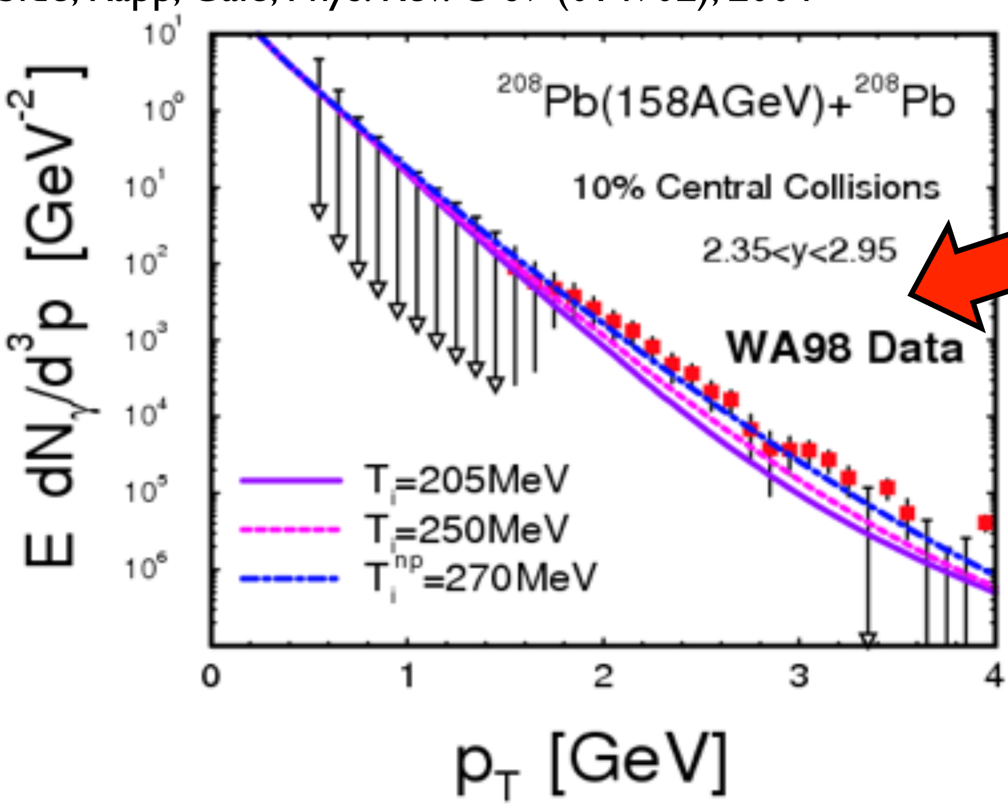
Ch. Gale, arXiv:0904.2184

Interplay between *T* ad k_T, contribution from QGP small

Direct Photons at CERN SPS: T or k_T ?

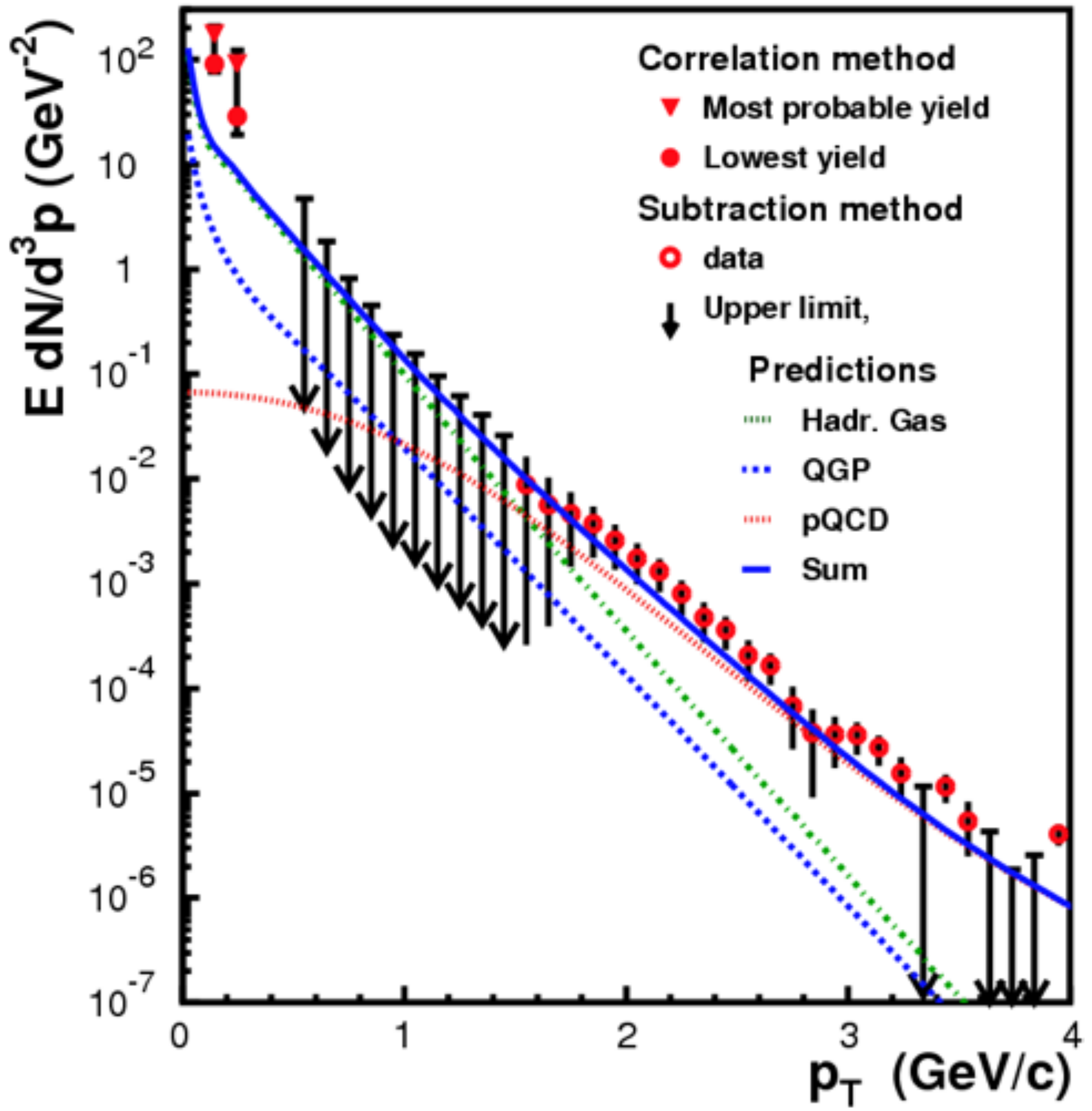


Turbide, Rapp, Gale, Phys. Rev. C 69 (014902), 2004



- QGP + HG rates convoluted with simple fireball model plus pQCD hard photons
- Data described with initial temperature T_i = 205 MeV
  + some nuclear k_T broadening (Cronin-effect)
- Data also described without k_T broadening but with high initial temperature (T_i = 270 MeV)

WA98: New low-p_T Points



WA98, Phys. Rev. Lett. 93 (022301), 2004

- Two-photon correlations observed and attributed to Bose-Einstein correlations of direct photons
- Correlation strength used to extract direct photon signal at low p_T
- Possible explanation: photon bremsstrahlung from hot hadron gas

  (Lui, Rapp, nucl-th/0604031)

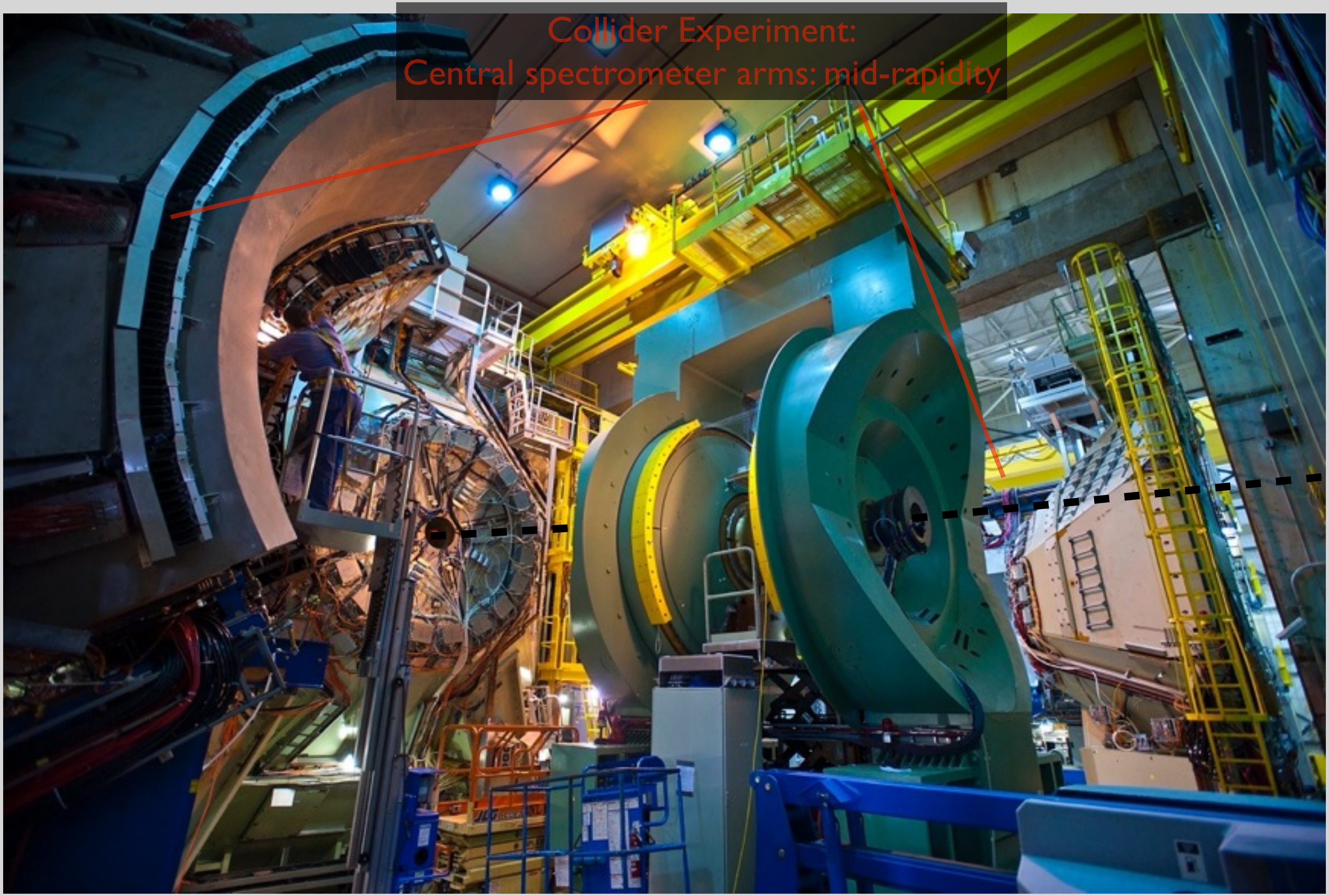
Direct Photons at CERN SPS: Conclusions

Data can be described under a variety of different assumptions, e.g.:

Turbide, Rapp, Gale (Phys.Rev.C69:014903,2004)	QGP + HG + pQCD with	***T*** τ_0
	QGP + HG + pQCD without	***T***$_i$ τ_0
Renk (Phys.Rev.C67:064901,2003)	QGP + HG + pQCD	250 < 0,5 <
Svrivastava (nucl-th/0411041)	QGP + HG + pQCC (Bjorken hydro)	***T*** τ_0
Huovinen, Ruuskanen, Räsänen (Nucl. Phys. A 650 (227) 1999)	QGP + HG + pQCD (Non-boost inv. hydro)	***T***$_i$
	Pure HG + pQCD (Non-boost inv. hydro)	***T***$_i$

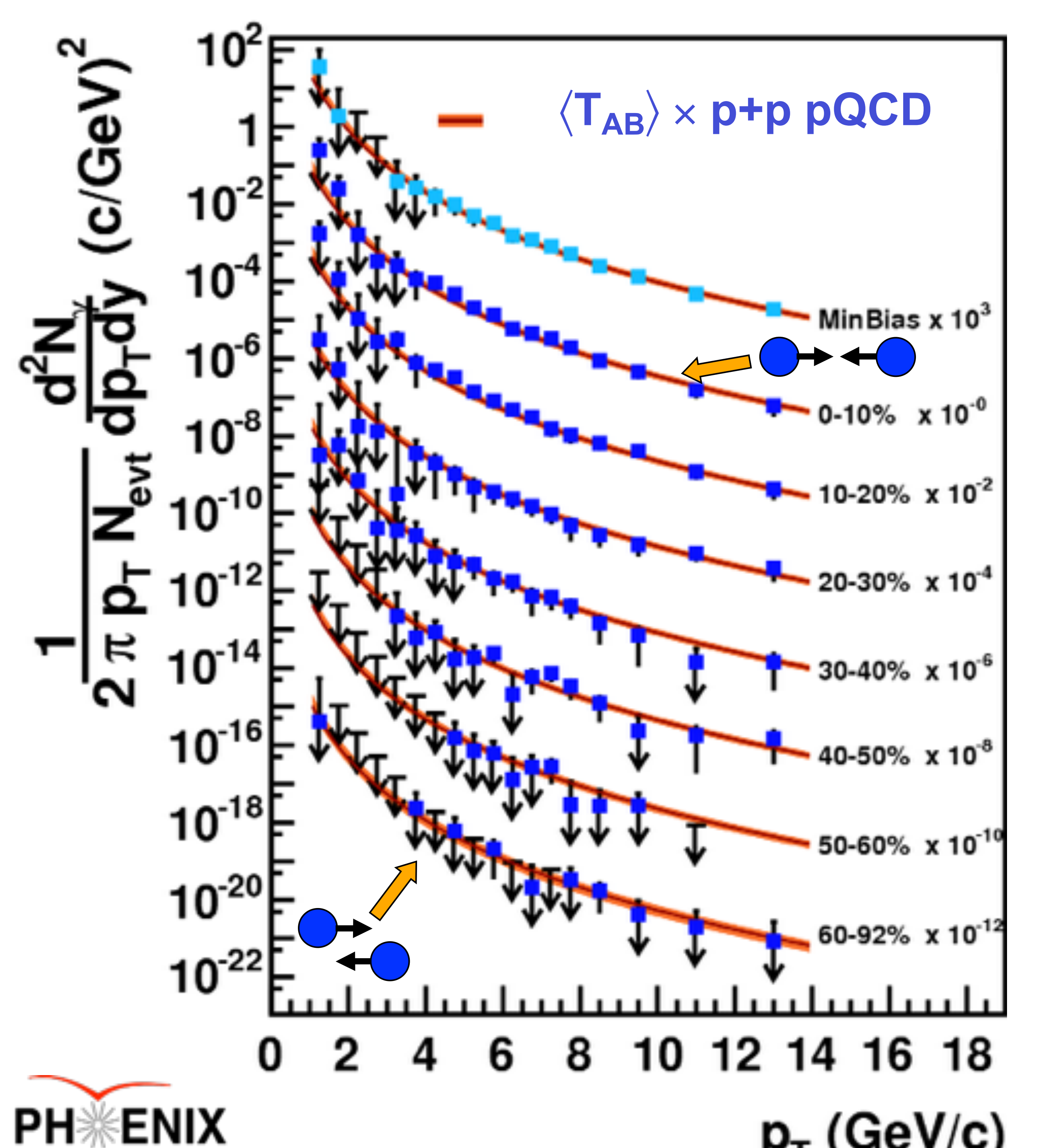
- Data consistent with QGP picture, but also with pure HG picture
- Large variations in extracted initial temperature T_i (however, most models give $T_i > T_c$)

Reminder: PHENIX detector



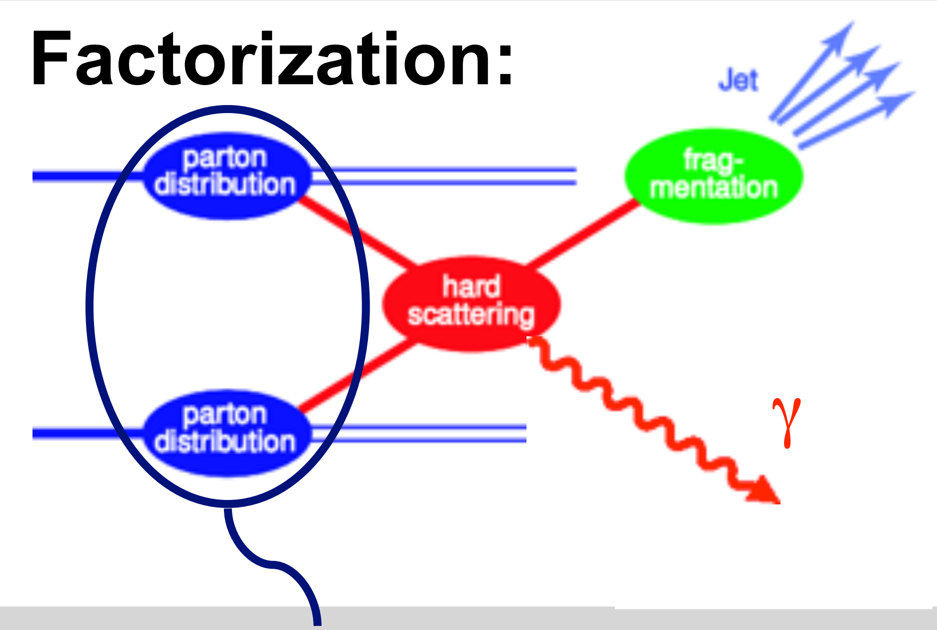
Direct-Photon Spectra in Au+Au

Au+Au at $\sqrt{s_{NN}}$ = 200 GeV (RHIC run 2)

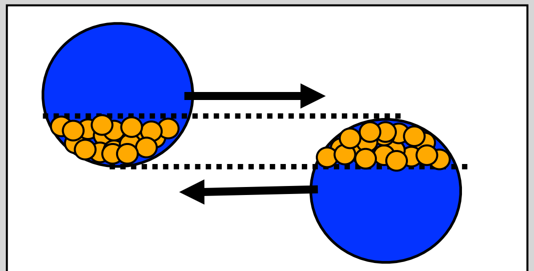


Phys.Rev.Lett.94:232301,2005

Factorization:



T_{AB} **: increase in parton-luminosity per event (p+p → Au+Au)**



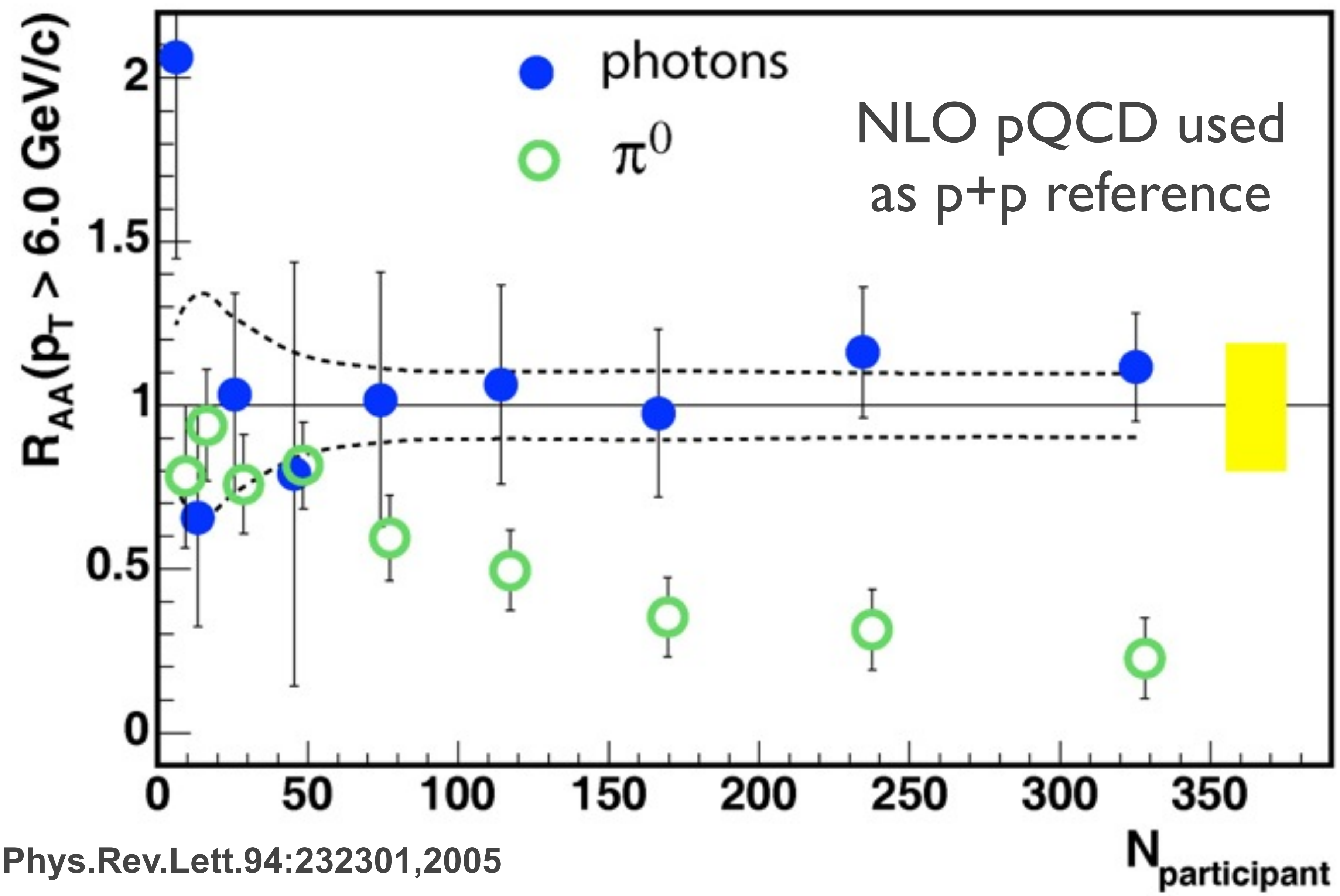
$$T_{AB} = N_{coll}/\sigma_{NN}^{inel}$$

0 – 10%:
$\langle N_{coll} \rangle$ = 955 ± 94

60 – 92%:
$\langle N_{coll} \rangle$ = 14.5 ± 4

- **High-p_T direct photons scale with $\langle T_{AB} \rangle$**
- **No indication of nuclear effects**

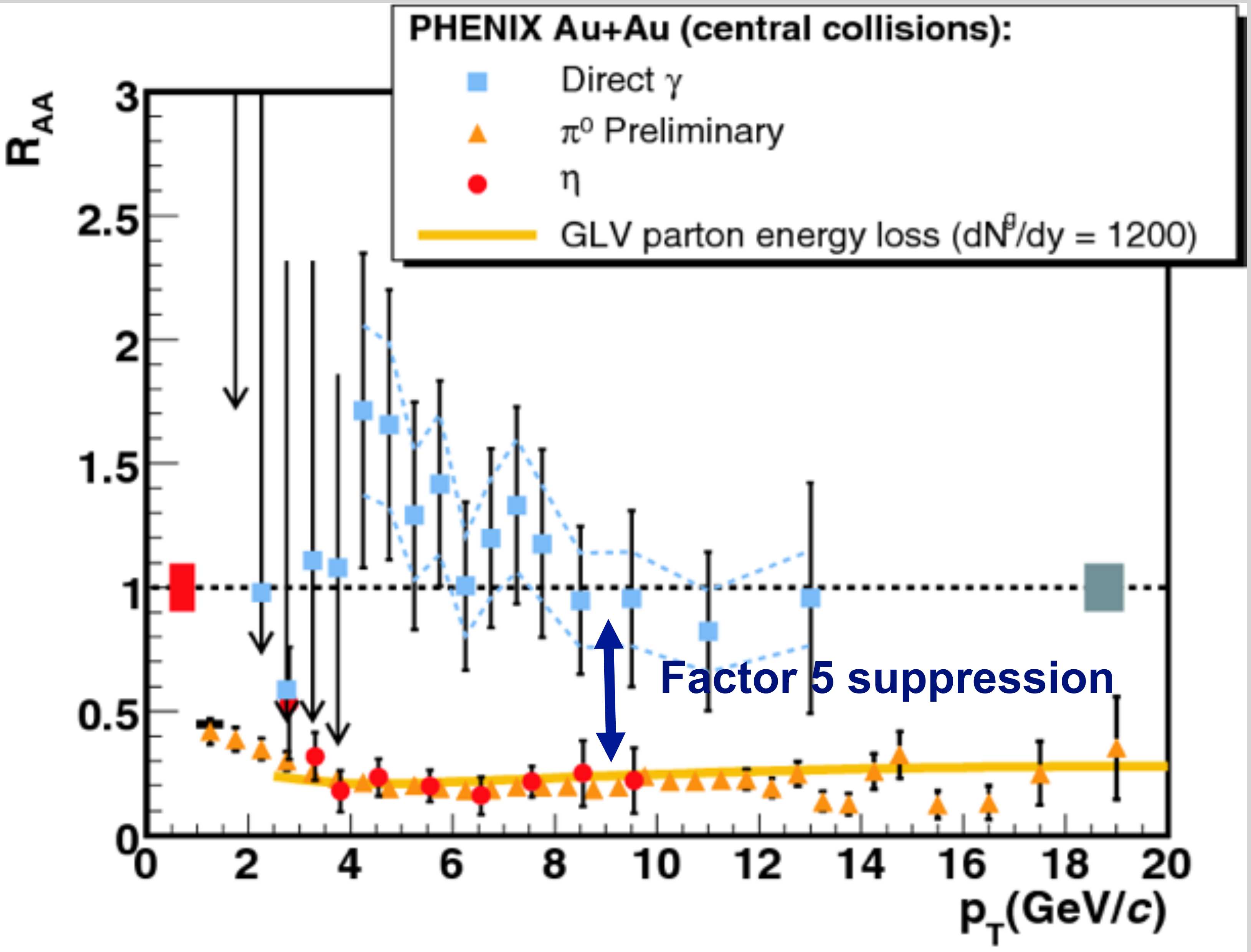
Centrality Dependence of the Direct Photon and π^0 R_{AA} in Au+Au Collisions at 200 GeV



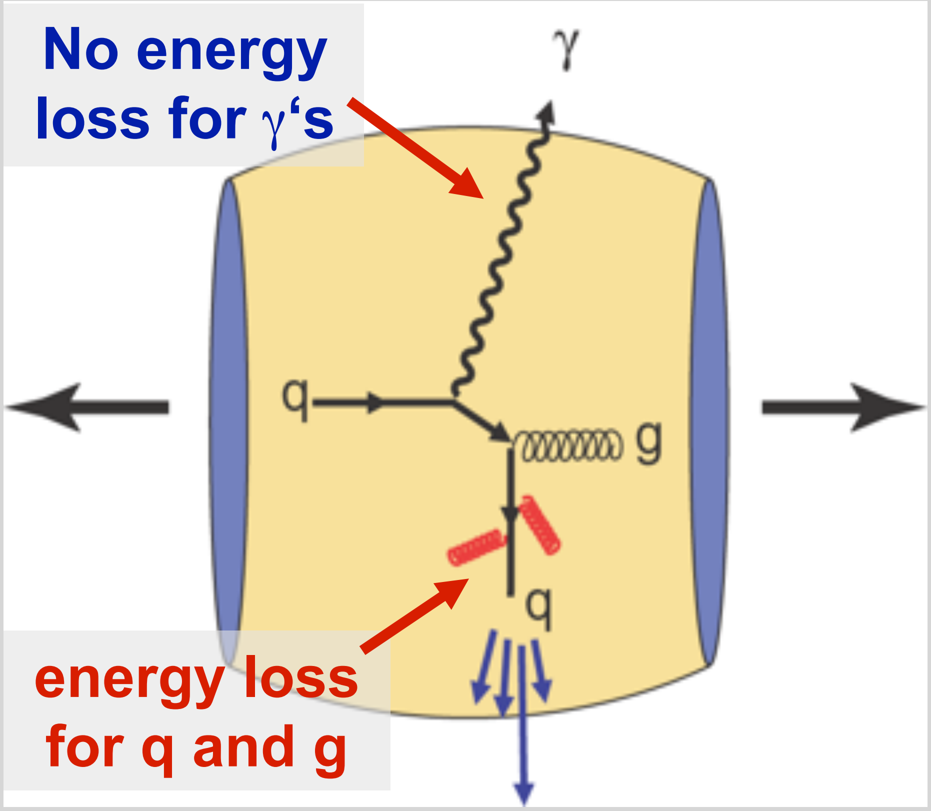
Phys.Rev.Lett.94:232301,2005

Direct photons follow T_{AB} scaling

Hadron Suppression: A Final State Effect!

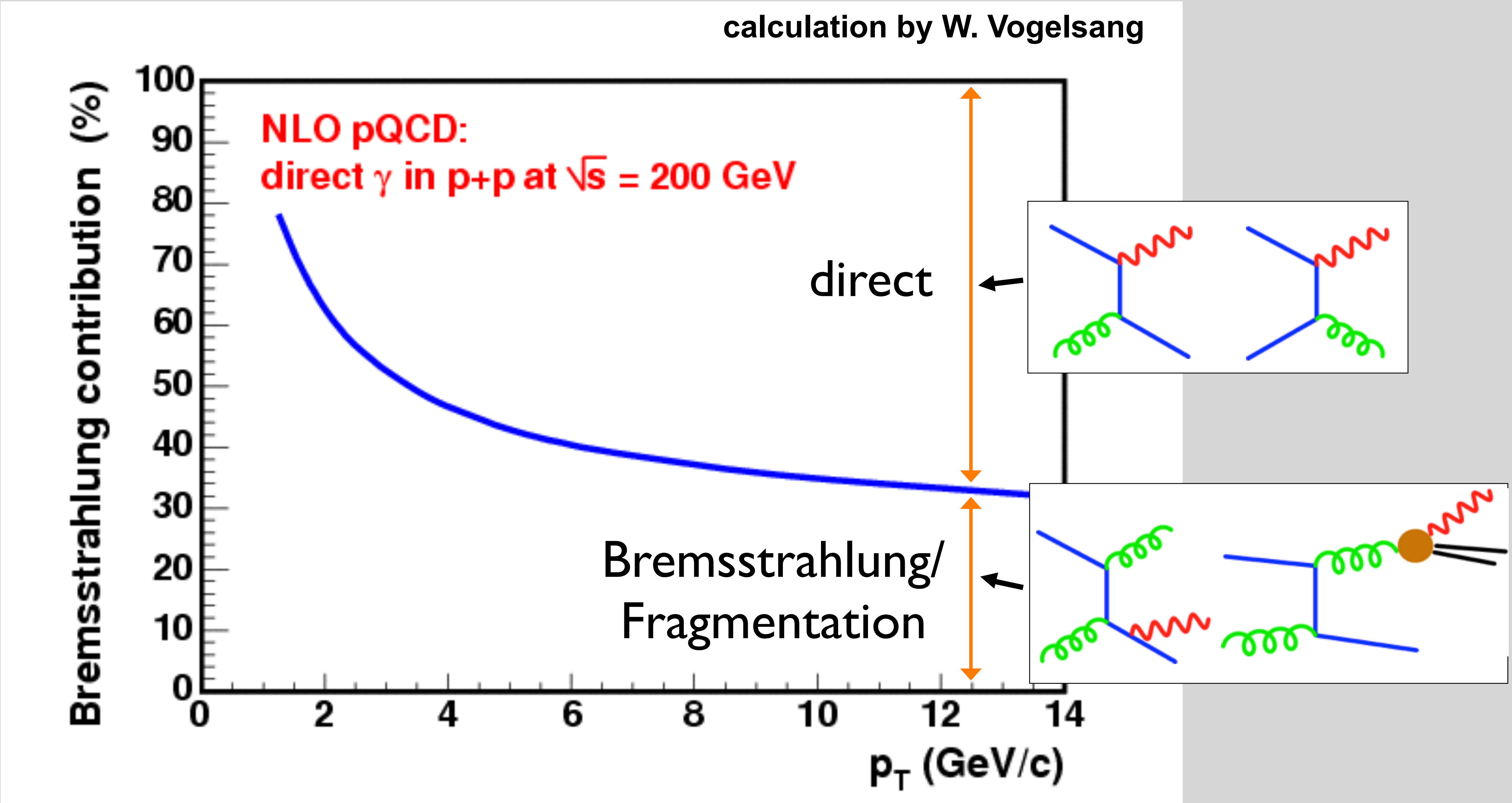


$$R_{AA} = \frac{dN/dp_T(A+A)}{\langle T_{AA} \rangle \times d\sigma/dp_T(p+p)}$$



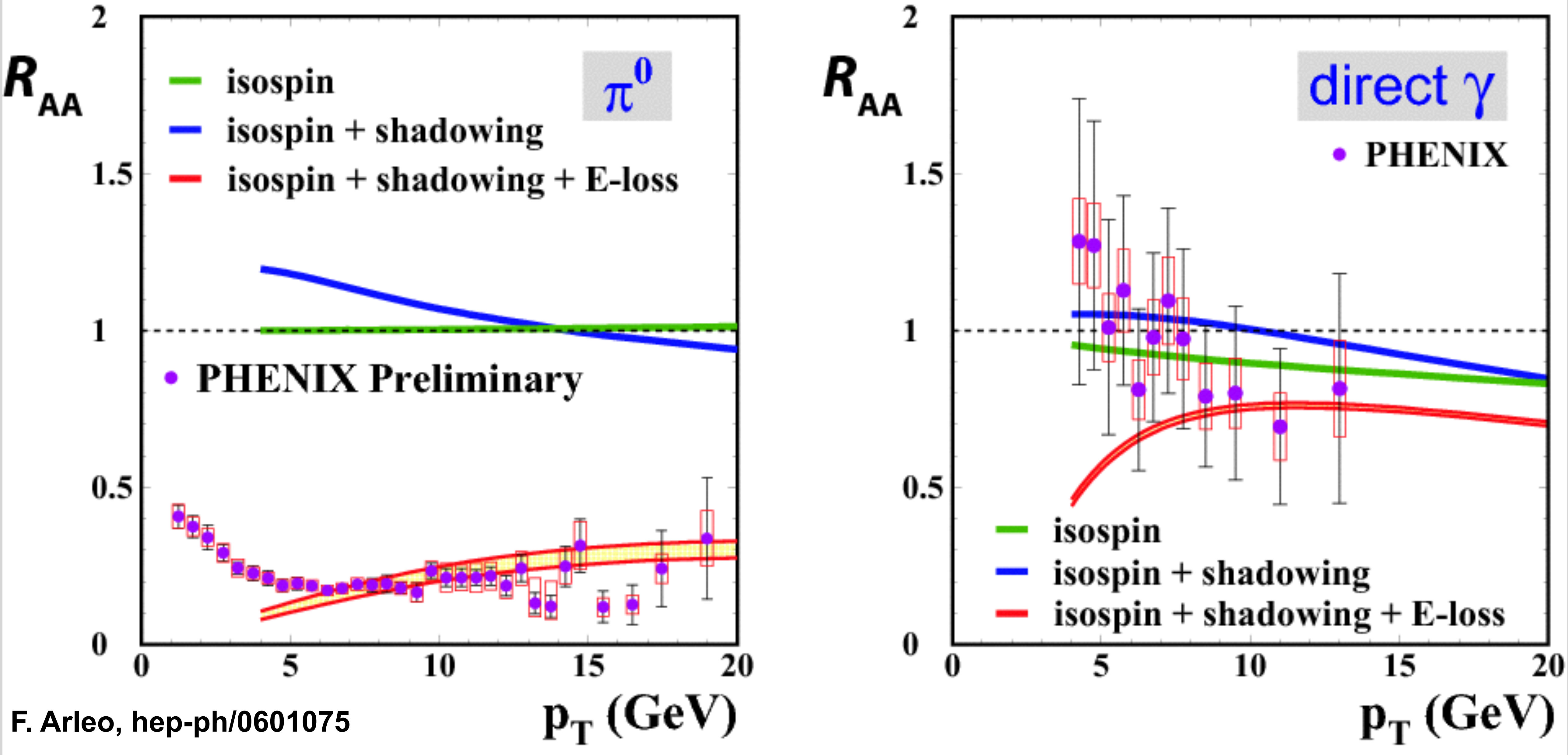
Hadrons are suppressed, but direct photons are not: Evidence for parton energy loss (as expected in the QGP)

pQCD: Bremsstrahlung/Fragmentation Component



- Bremsstrahlung/fragmentation contribution large
- Suppression of bremsstrahlung/fragmentation contribution expected in A+A

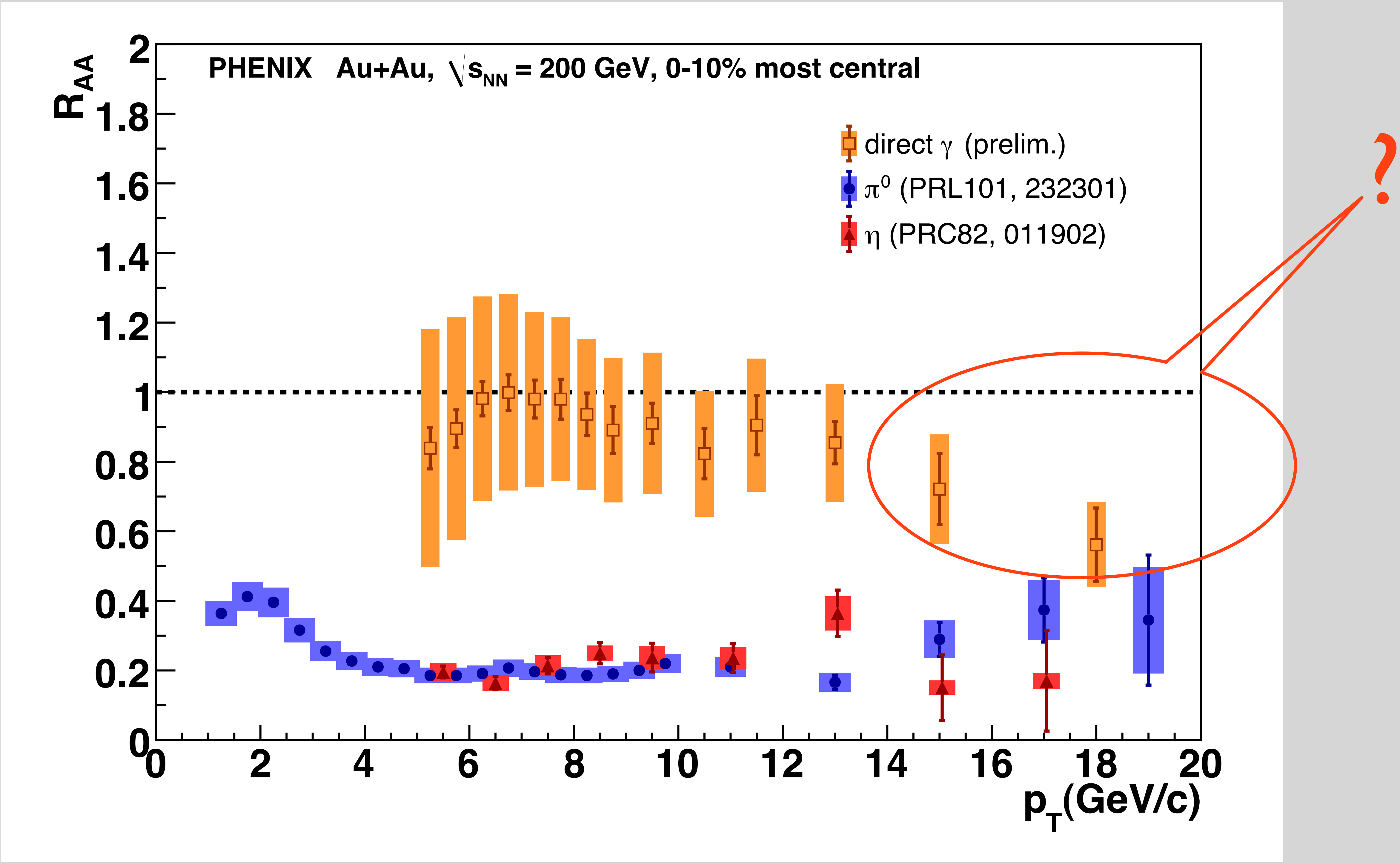
Effect of Parton Energy Loss



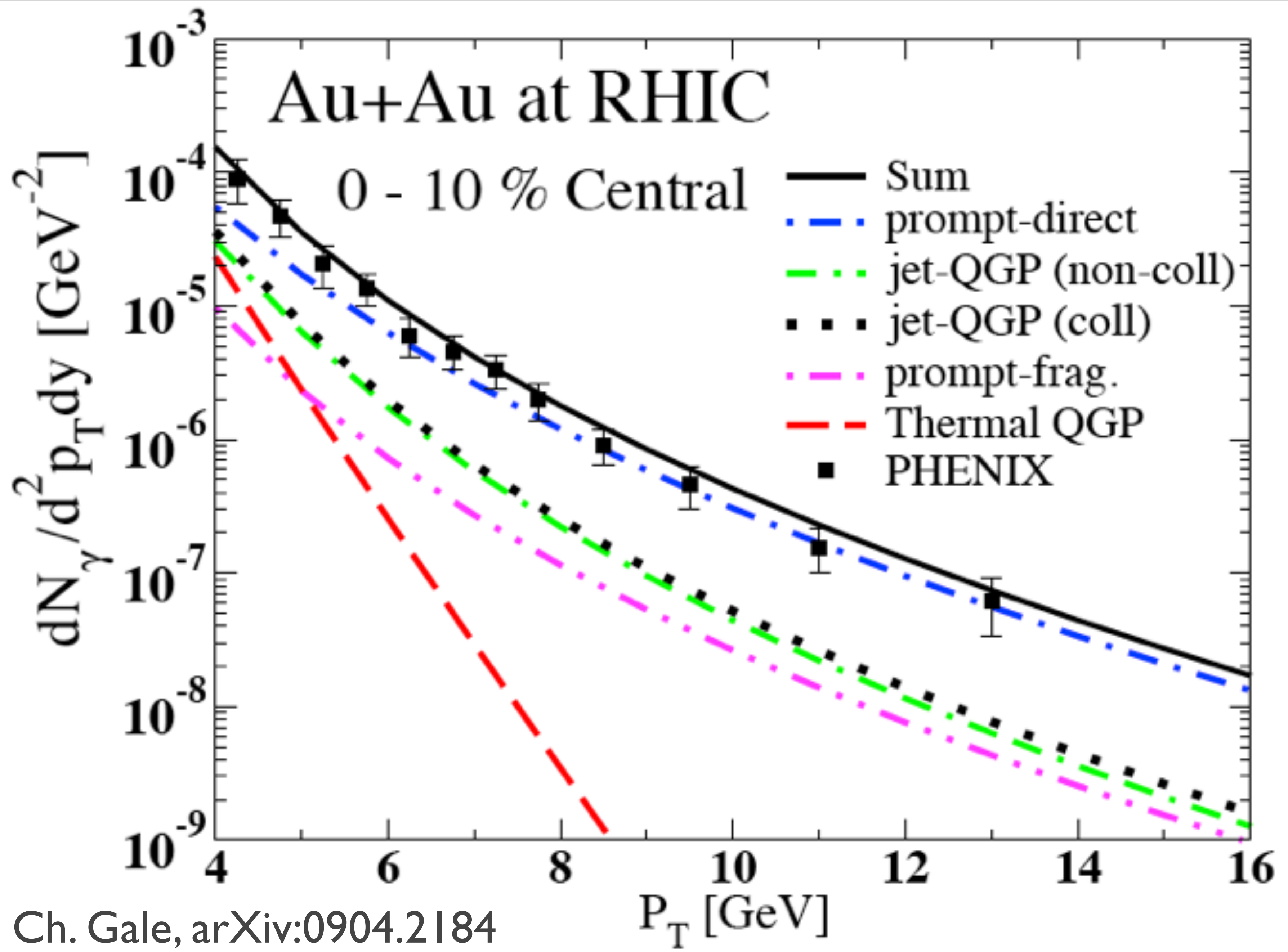
F. Arleo, hep-ph/0601075

- 20-30% reduction of direct photon R_{AA} expected due to parton energy loss
- Consistent with PHENIX data

The Puzzle of the Preliminary Direct Photon R_{AA} at high p_T (PHENIX, Run 4 Au+Au data)



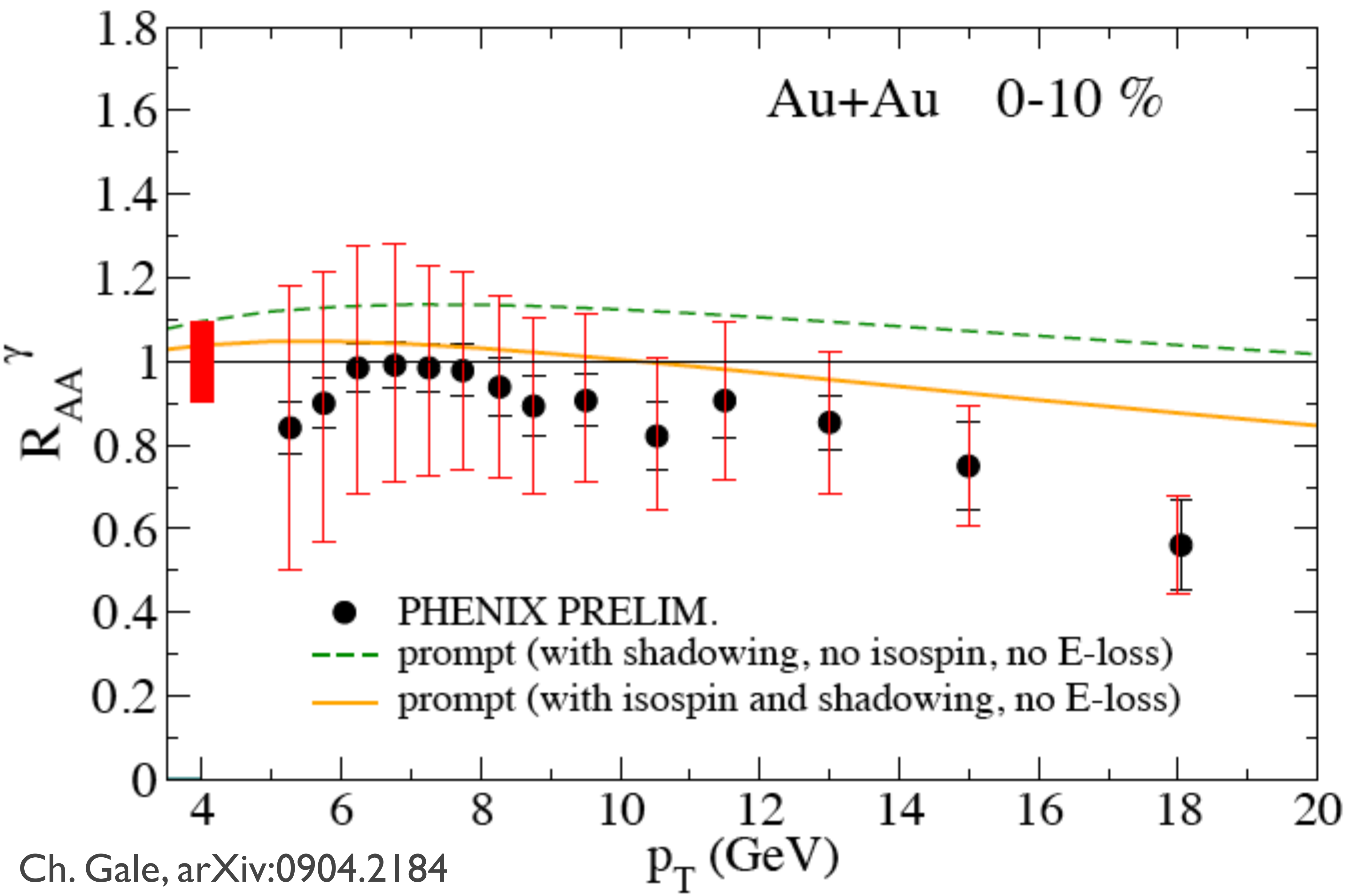
Interpretation of the Direct-Photon Spectrum at RHIC (p_T > 4 GeV/c) (I)



Ch. Gale, arXiv:0904.2184

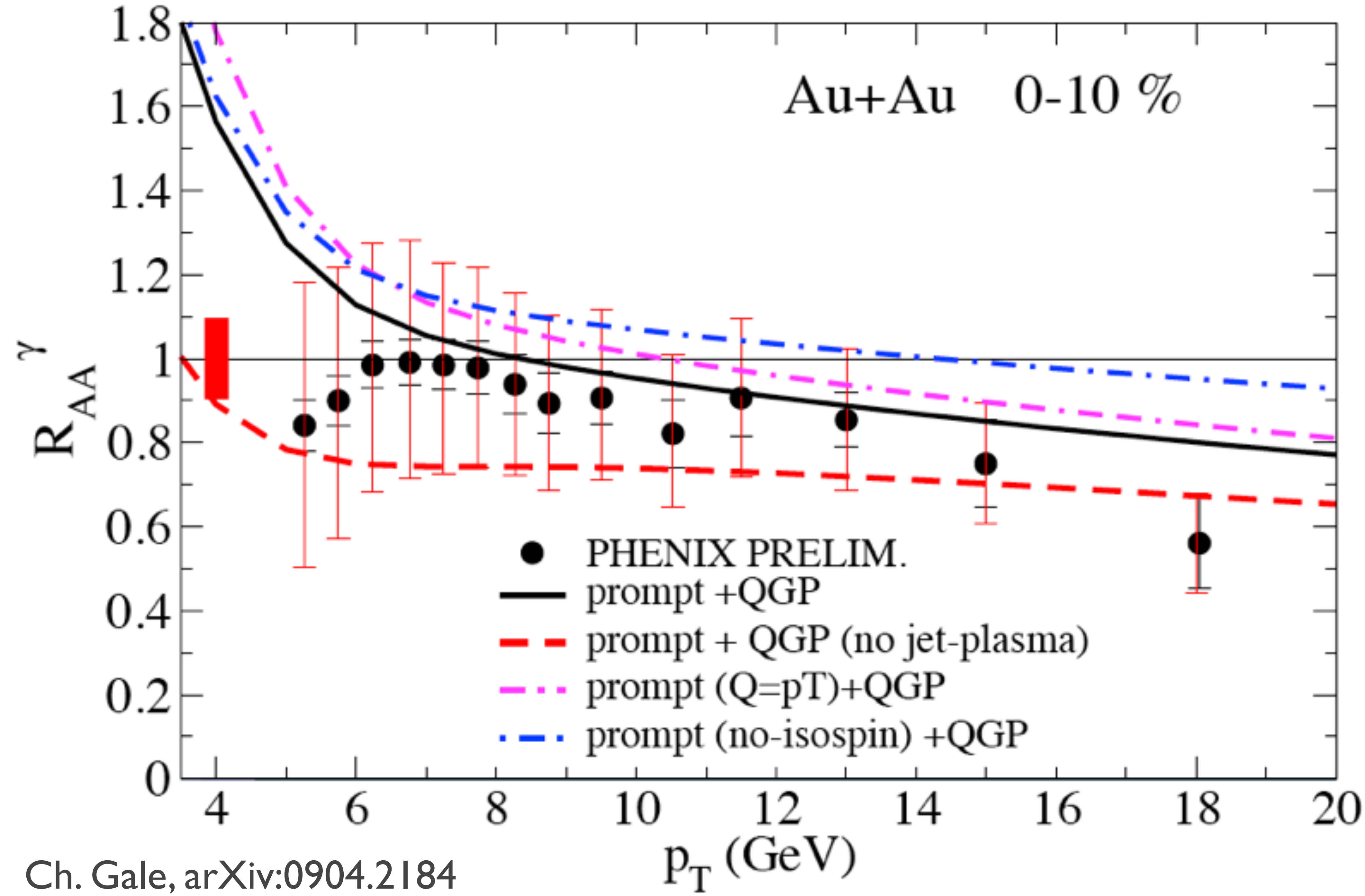
Indication for relevance of photons from jet-plasma interactions for p_T < 6 GeV/c ?

Interpretation of the Direct-Photon Spectrum at RHIC (p_T > 4 GeV/c) (II)



Ch. Gale, arXiv:0904.2184

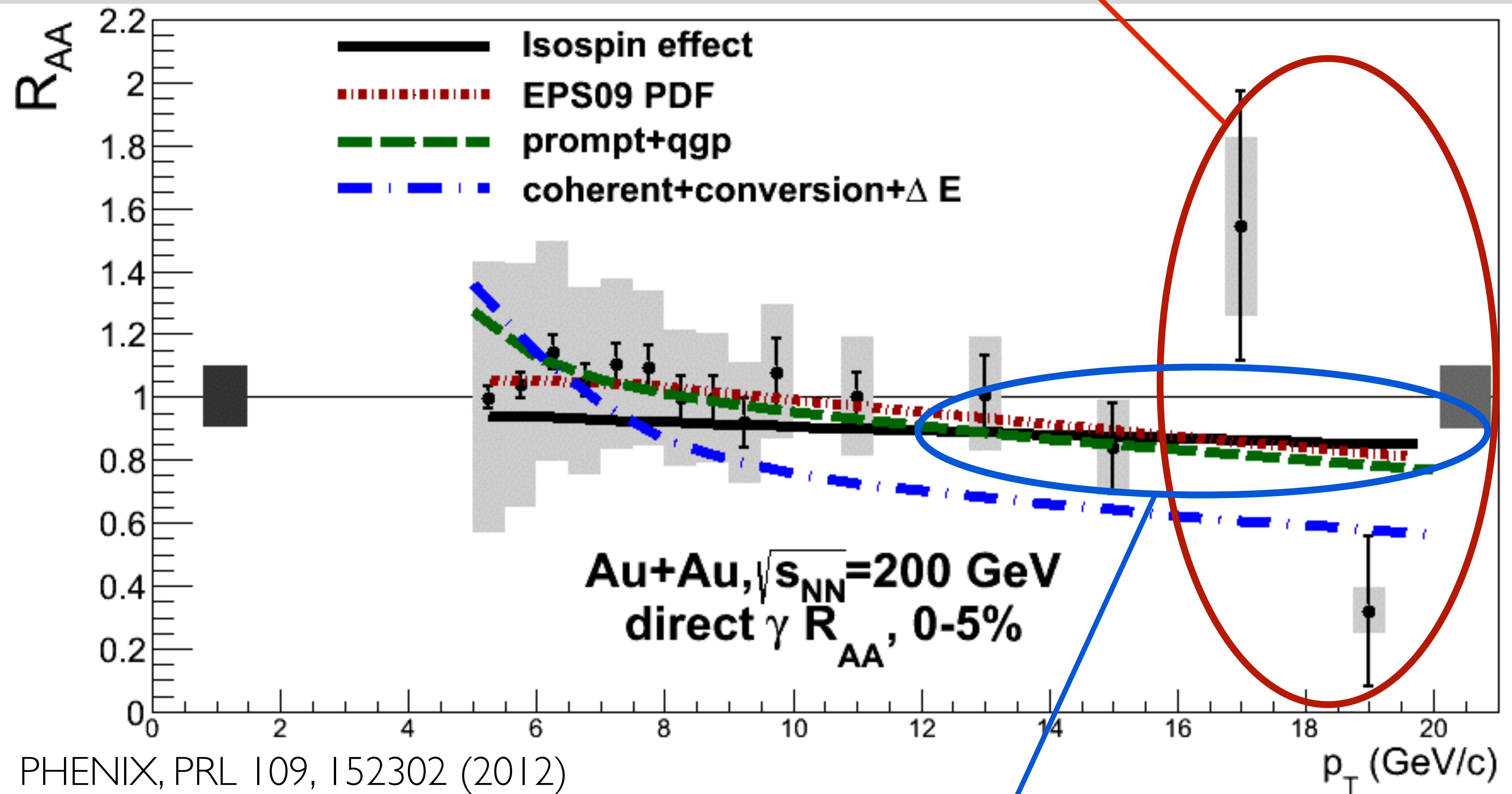
Interpretation of the Direct-Photon Spectrum at RHIC (p_T > 4 GeV/c) (III)



Ch. Gale, arXiv:0904.2184

And Now: The Final Results

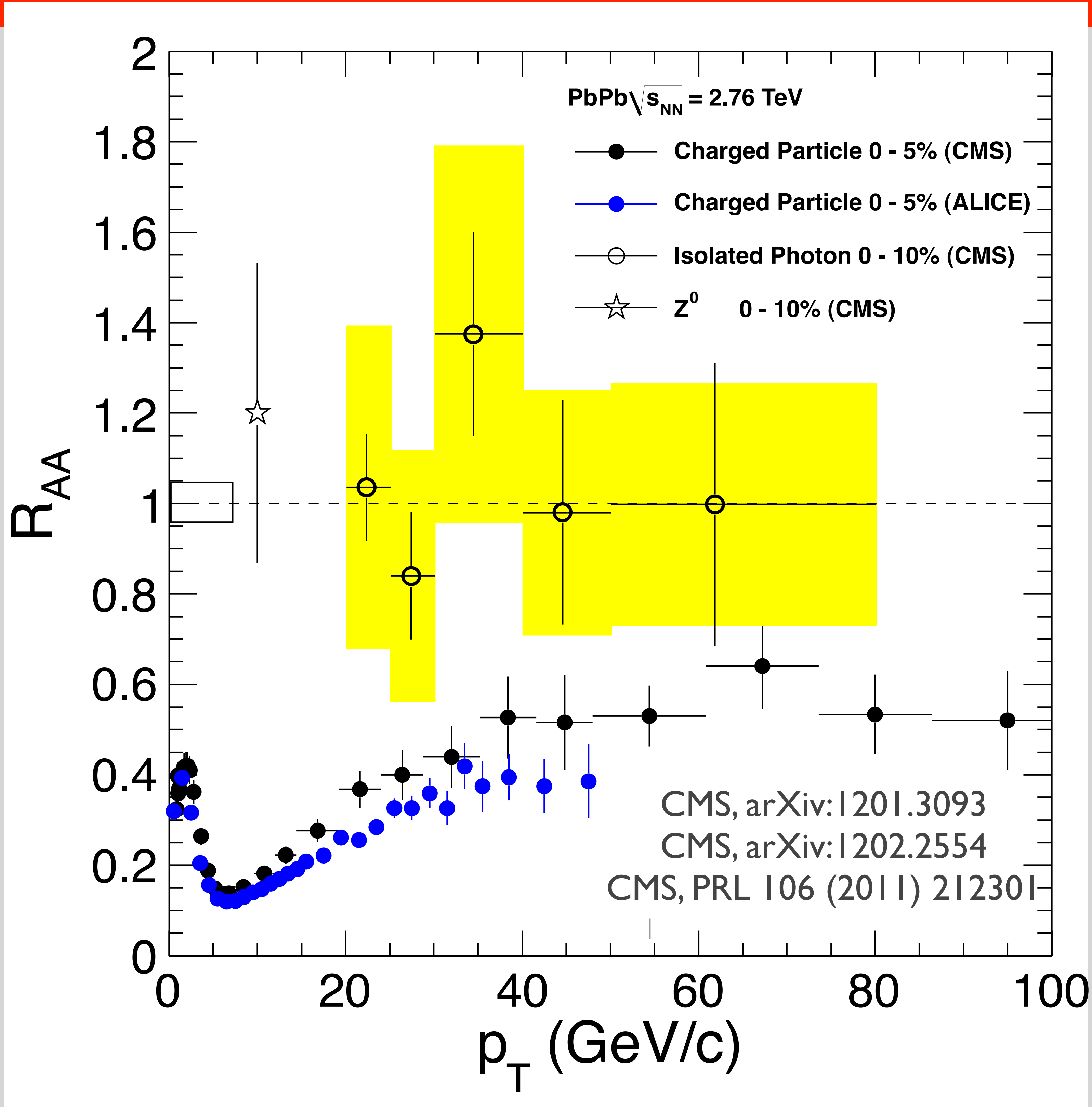
Looks like statistical fluctuations



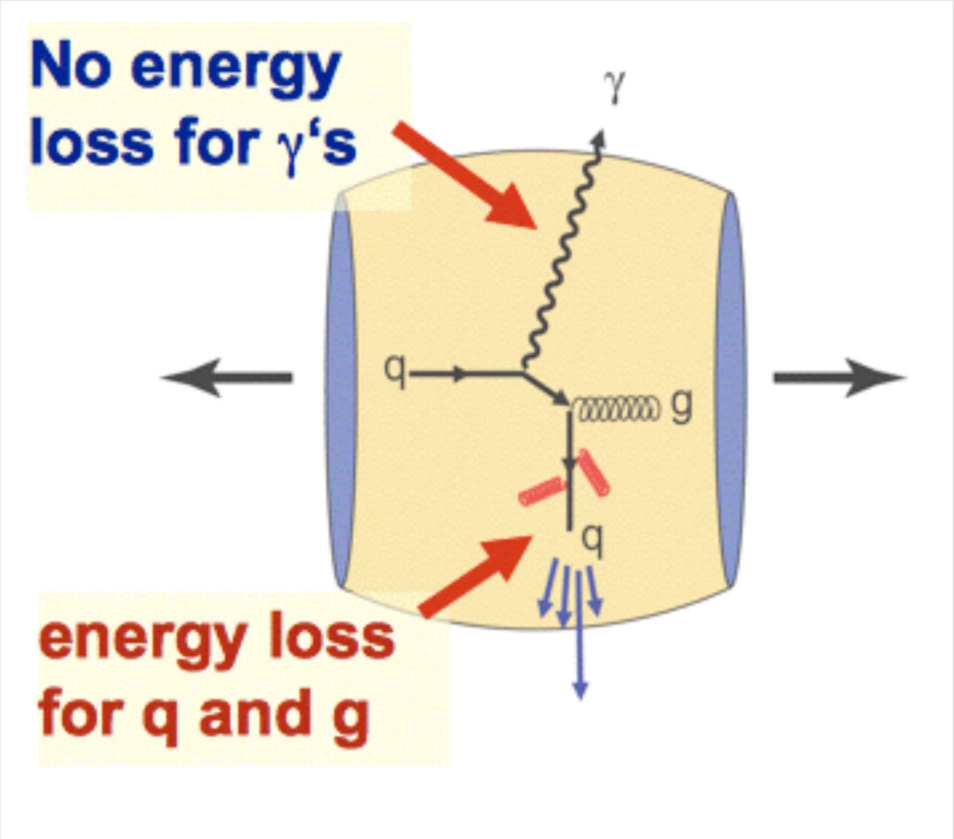
PHENIX, PRL 109, 152302 (2012)

The effects from the QGP appear to cancel

Pb+Pb at the LHC: Test of T_{AA} Scaling With Prompt Photons (and Z)

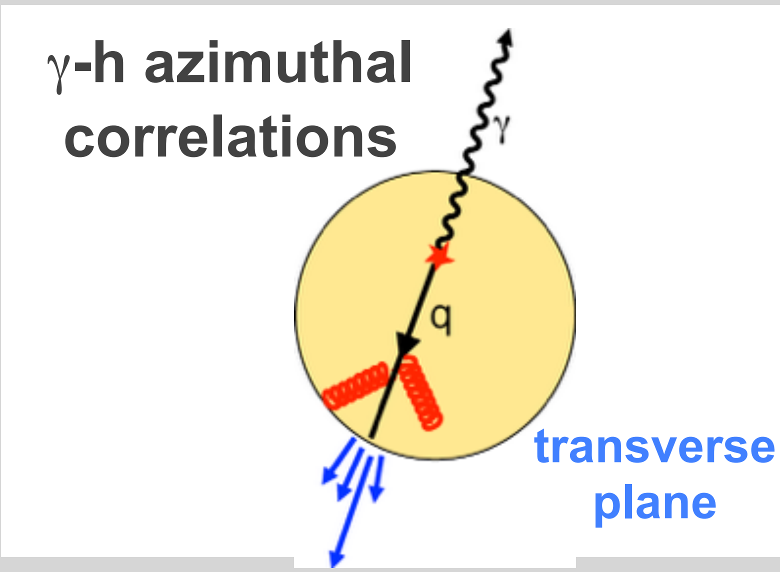


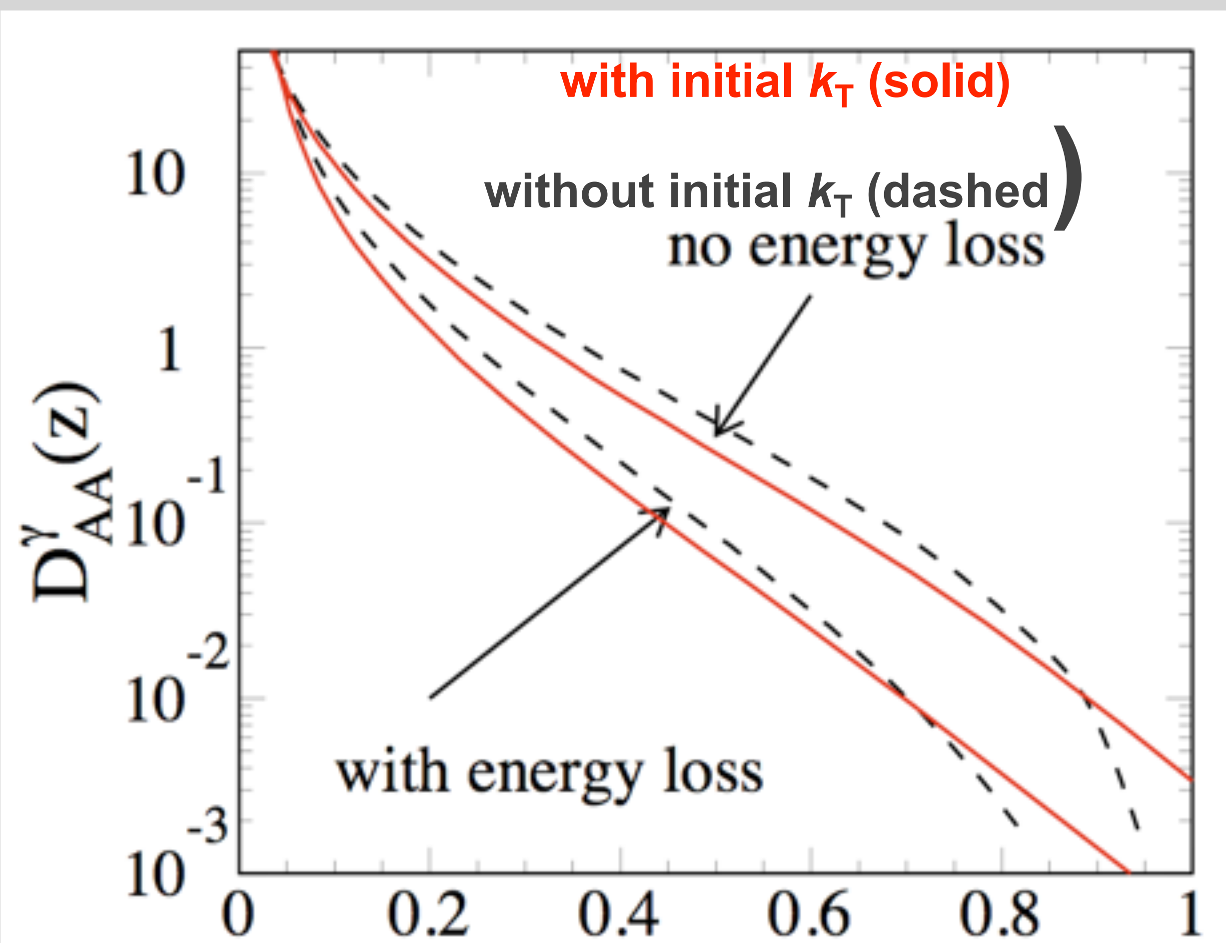
$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$



Prompt Photons (and Z^0's) are not suppressed: Strong Evidence for Parton Energy Loss Picture

γ-Triggered Away-Side Correlations: Basic Idea





Wang, Huang, Phys.Rev.C55:3047-3061,1997

- p+p:
  (Effective) jet fragmentation functions can be extracted from γ-hadron azimuthal correlations (modulo initial k_T effect)

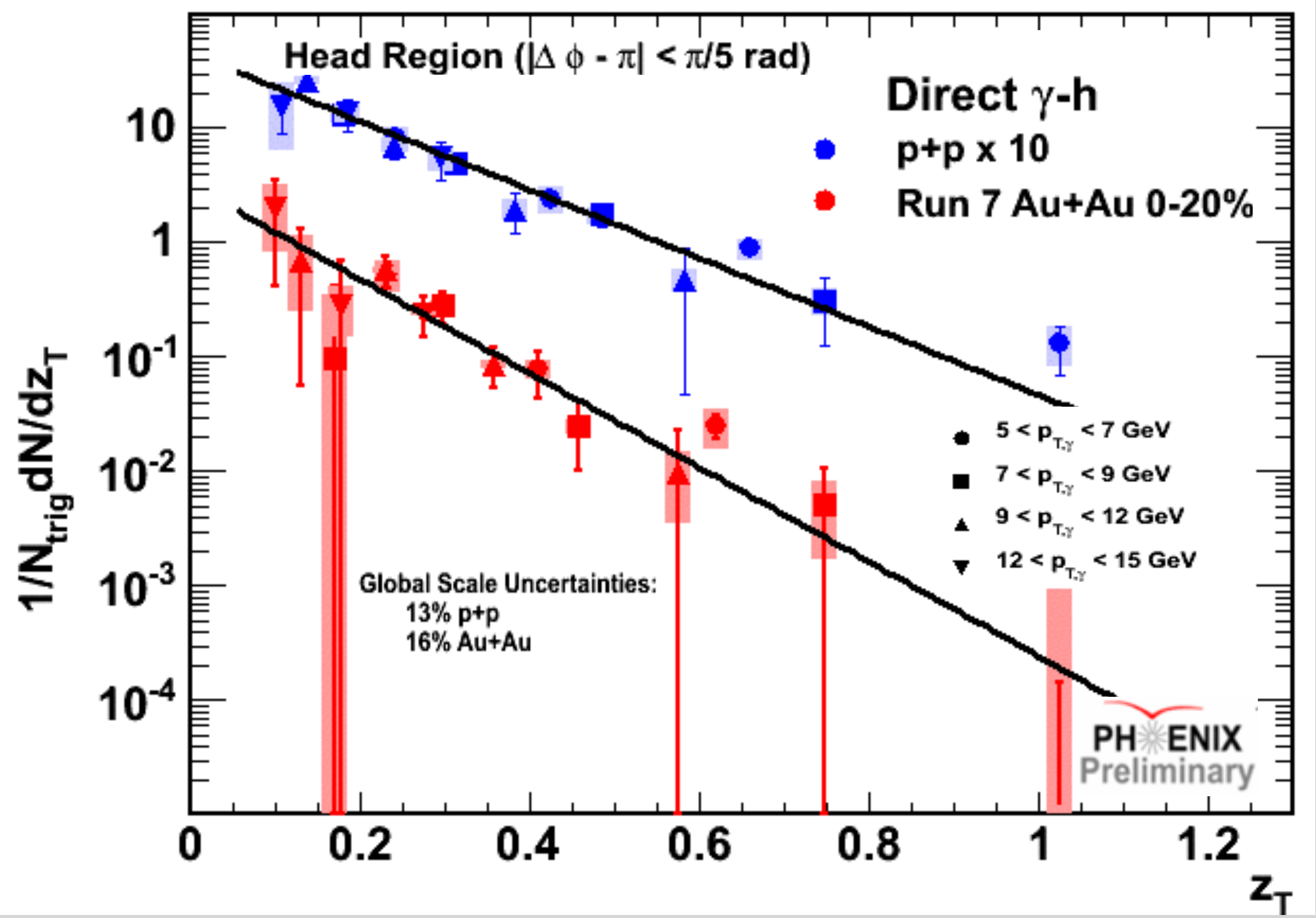
- A+A:
  Modification of fragmentation function provides information on parton energy loss

- Variables:

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$D(z_T) = \frac{1}{N_{\text{trig}}} \frac{dN(z_T)}{dz_T}$$

γ-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au



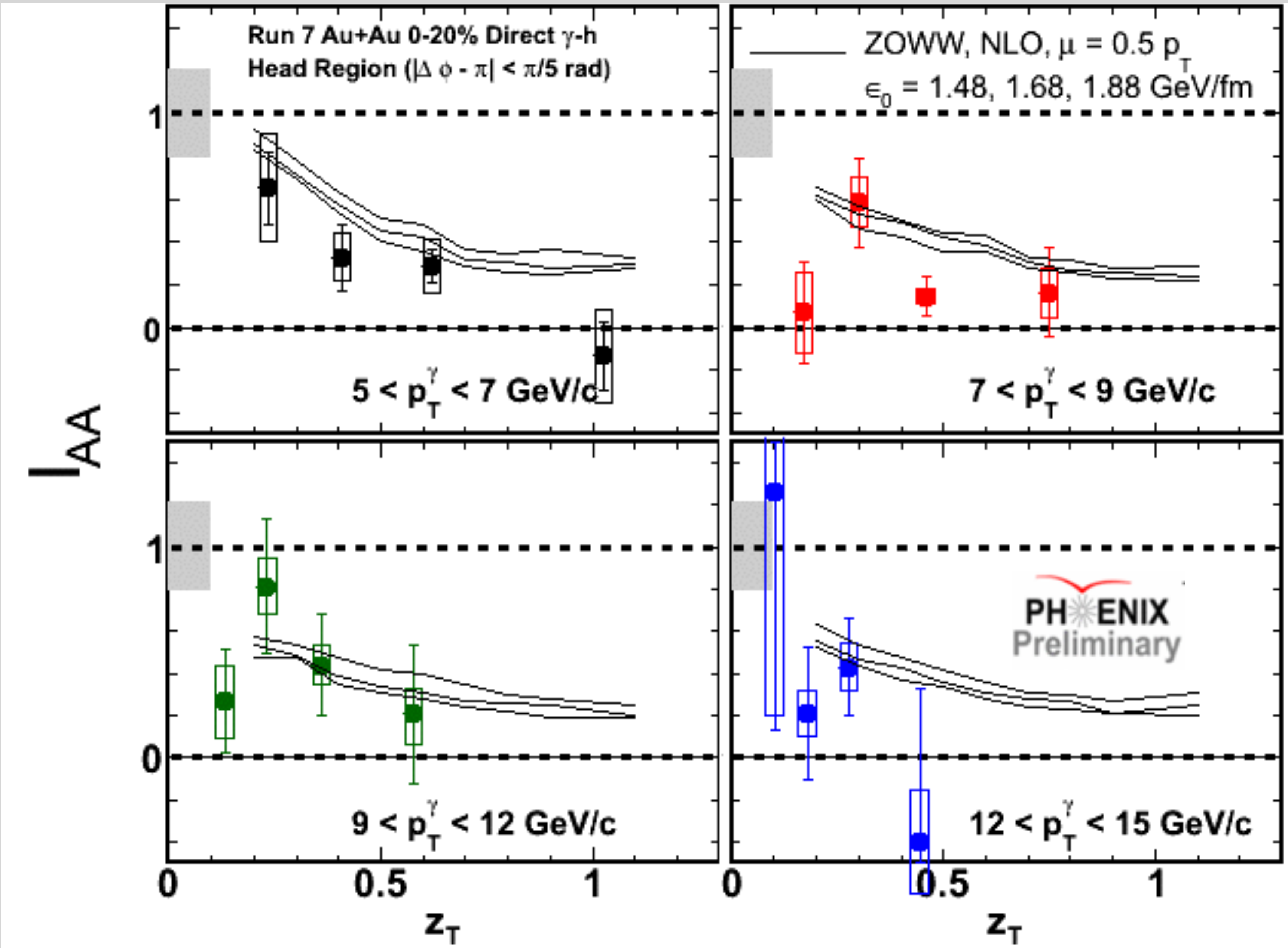
- Fit effective FF's with

$$\frac{dN}{dz_T} = Ne^{-bz_T}$$

- p+p: b = 6.89 ± 0.64
- Au+Au: b = 9.49 ±1.37
- Difference reflects influence of the medium

γ-Triggered Away-side Correlations: Results

$I_{AA} = D_{AA}(z_T) / D_{pp}(z_T)$



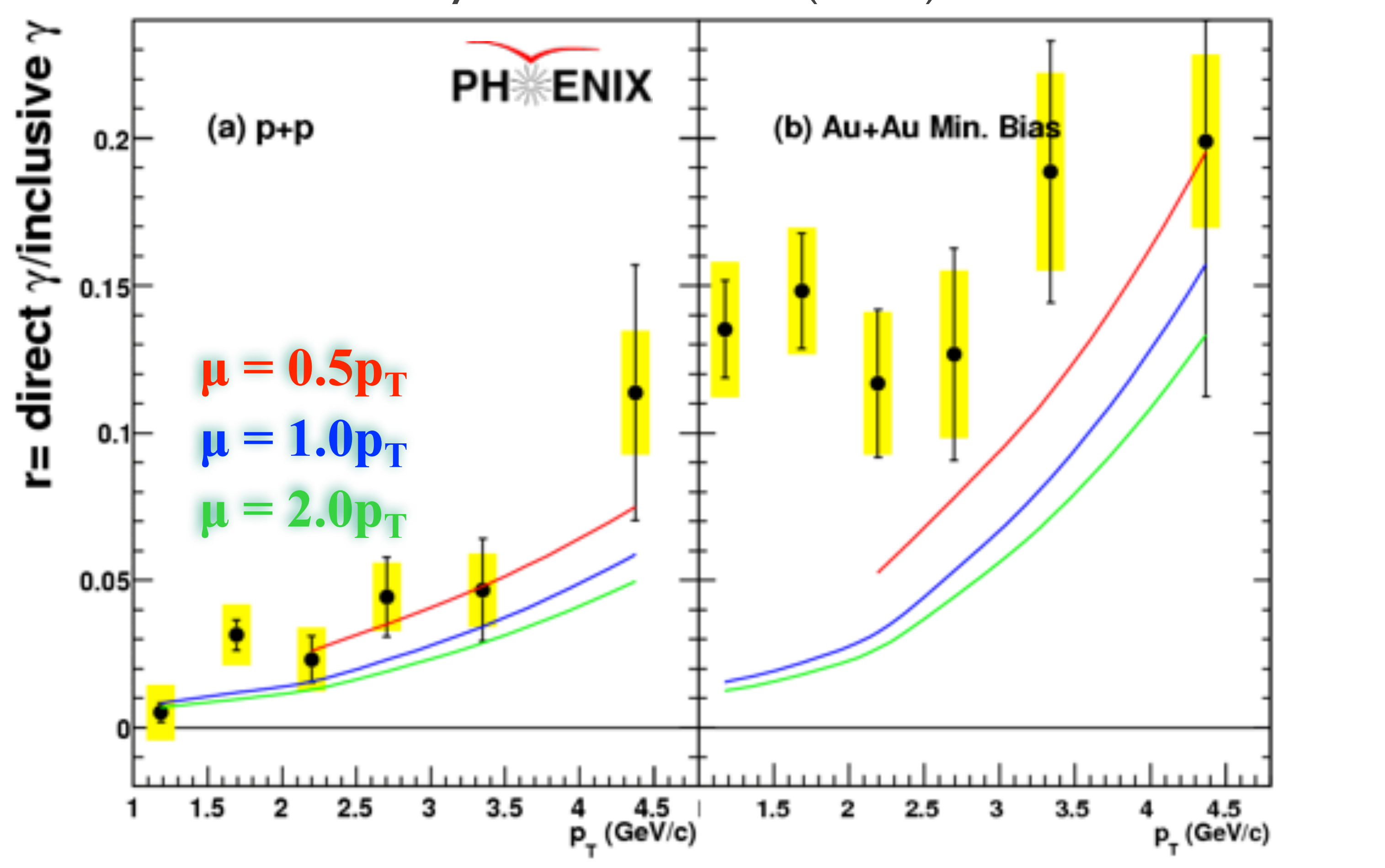
NLO calculation:
Zhang et al. (ZOWW), arXiv:0902.4000v1

- Different z_T regions probe different regions of the fireball (arXiv:0902.4000v1)
- Agreement with NLO pQCD + parton energy loss: Indication that energy loss in different regions of the fireball is understood

Thermal Region

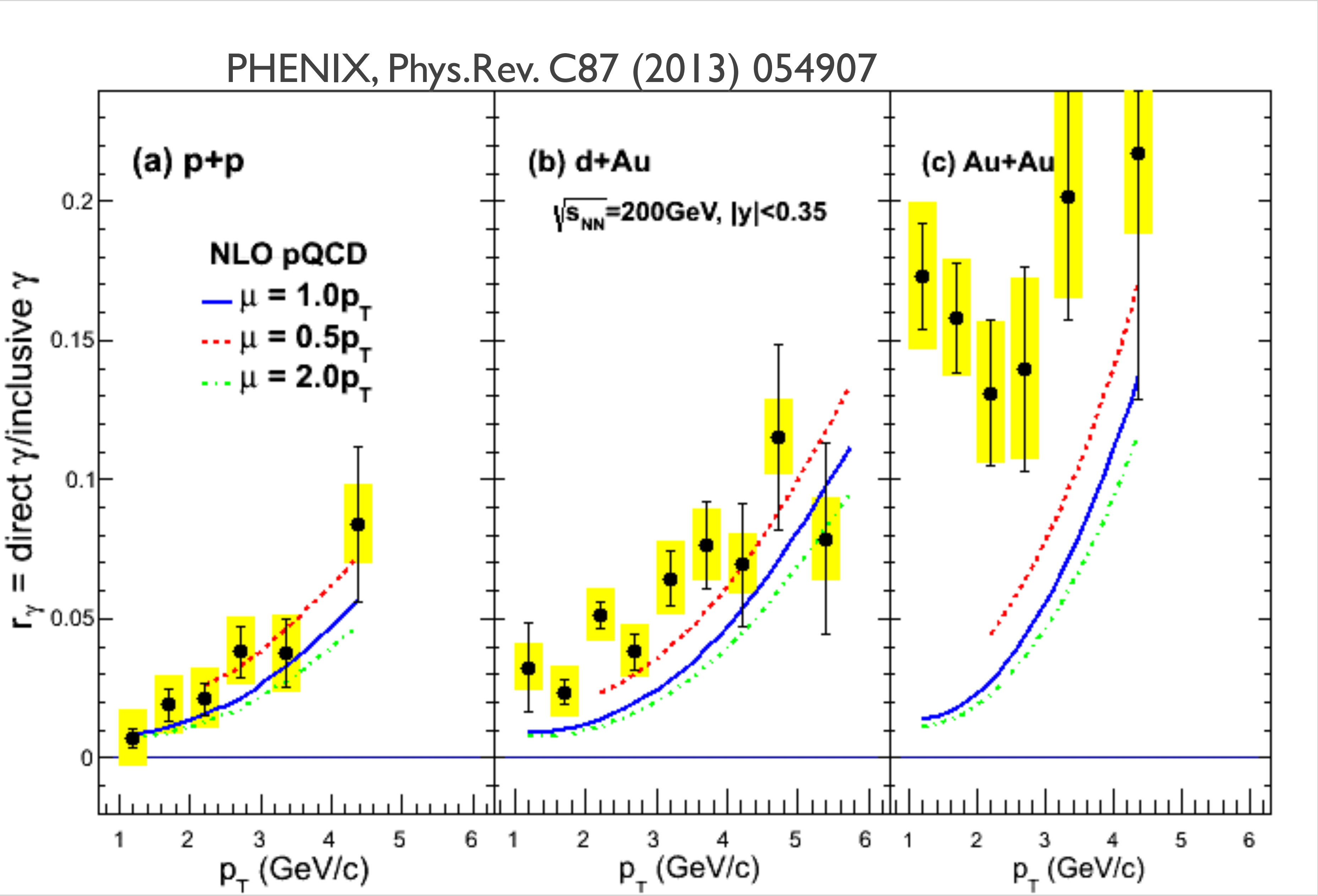
Direct Photon Fraction in p+p and Au+Au at $\sqrt{s_{NN}} = 200$ GeV

PHENIX, Phys.Rev.Lett. 104 (2010) 132301



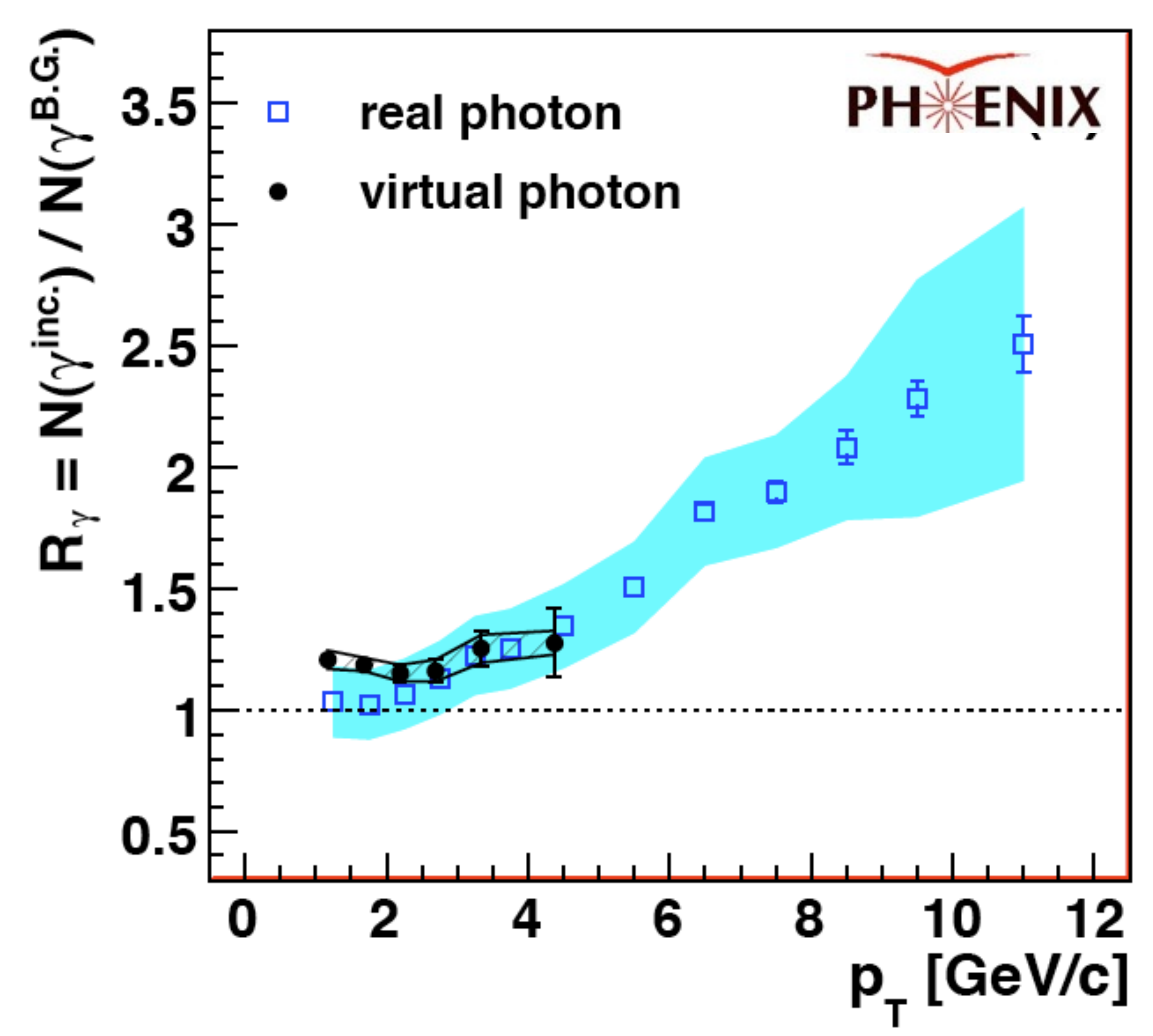
- Lowest p_T ever measured in p+p
- Comparison to NLO pQCD (colored lines)
- p+p: Agreement
- Au+Au: Strong enhancement at low p_T

Is it Initial State?

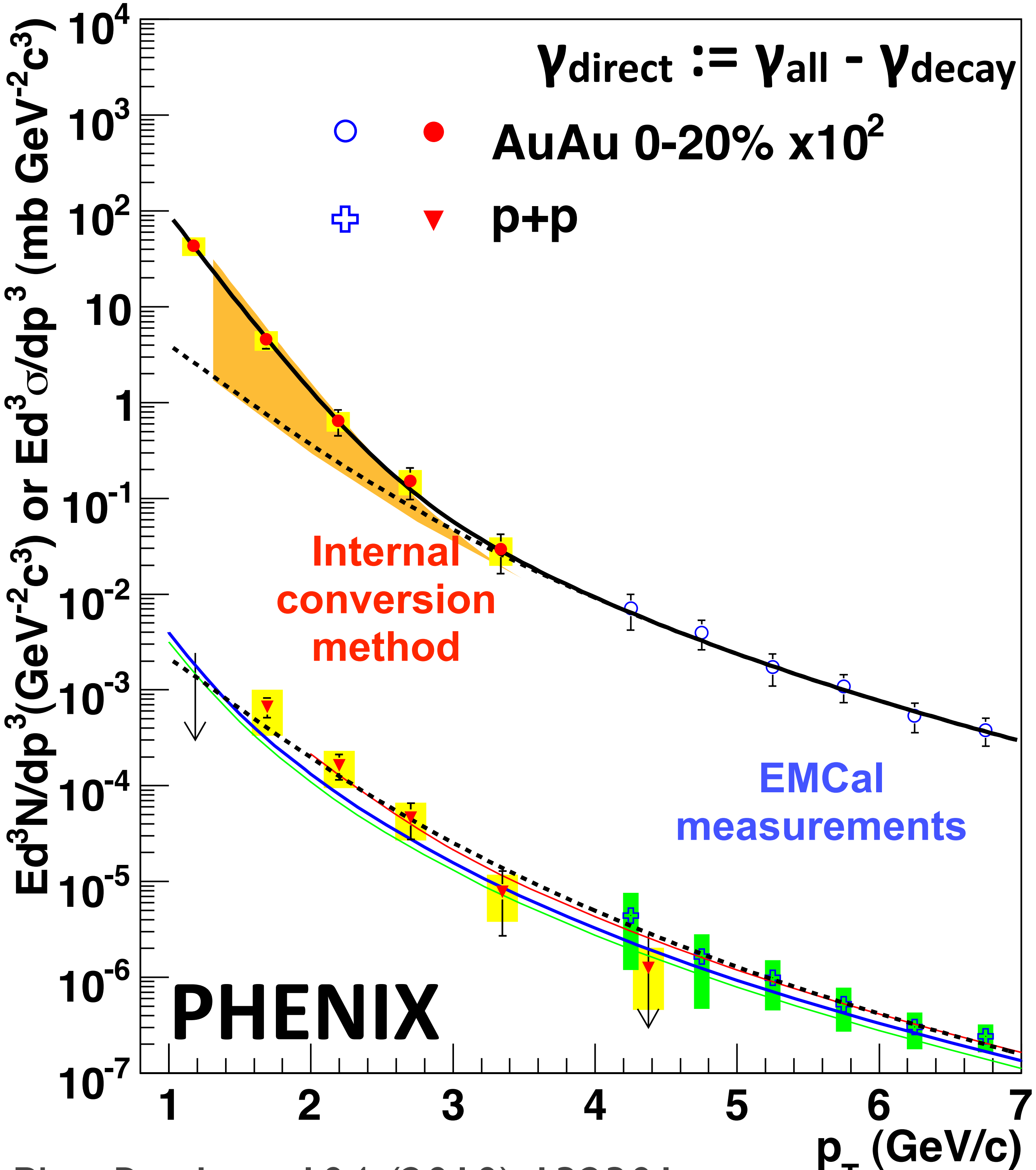


- Use d+Au collisions
- Same method: no significant low pT enhancement in such collisions
- Hints strongly that enhancement is final state effect in Au+Au

Comparison Between the Internal Conversion Method and the Calorimeter Measurement



Low p_T Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP



Phys.Rev.Lett. 104 (2010) 132301

- p+p: spectrum described with

$$f_{p+p}(p_T) = A \cdot (1 + p_T^2 / b)^{-n}$$

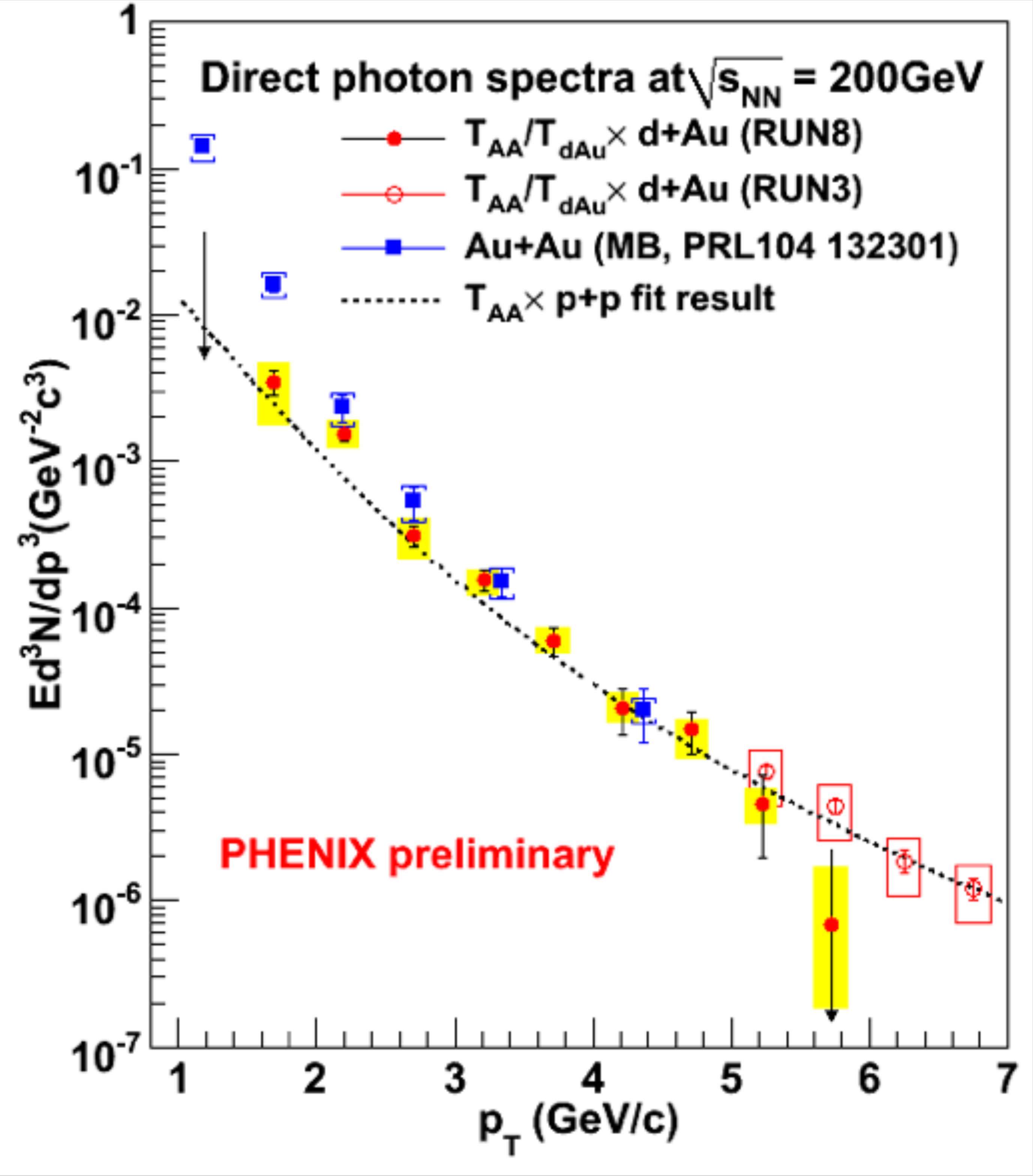
- Au+Au:
  Enhancement above p+p described by an exponential (as expected for a thermal source)

$$f_{Au+Au}(p_T) = \frac{N_{coll}}{\sigma_{NN}^{inel}} \times f_{p+p}(p_T) + B \times e^{-\frac{p_T}{T}}$$

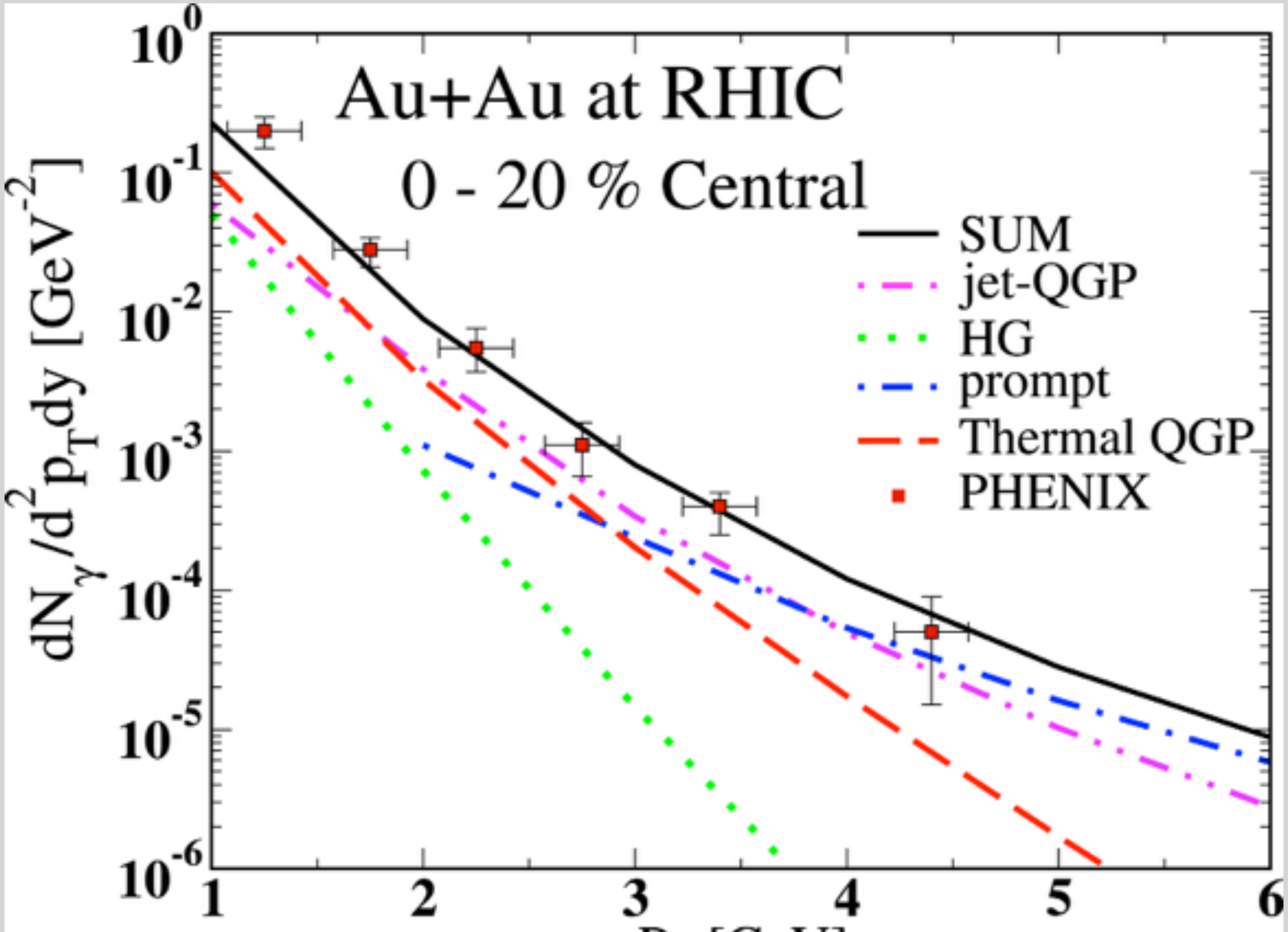
- Slope parameter (0-20%):
  T = (221 ± 23 ± 18) MeV

Historically expected to be a lower limit for the initial temperature!

Critical d+Au Check: No exponential excess in d +Au



Model Comparison

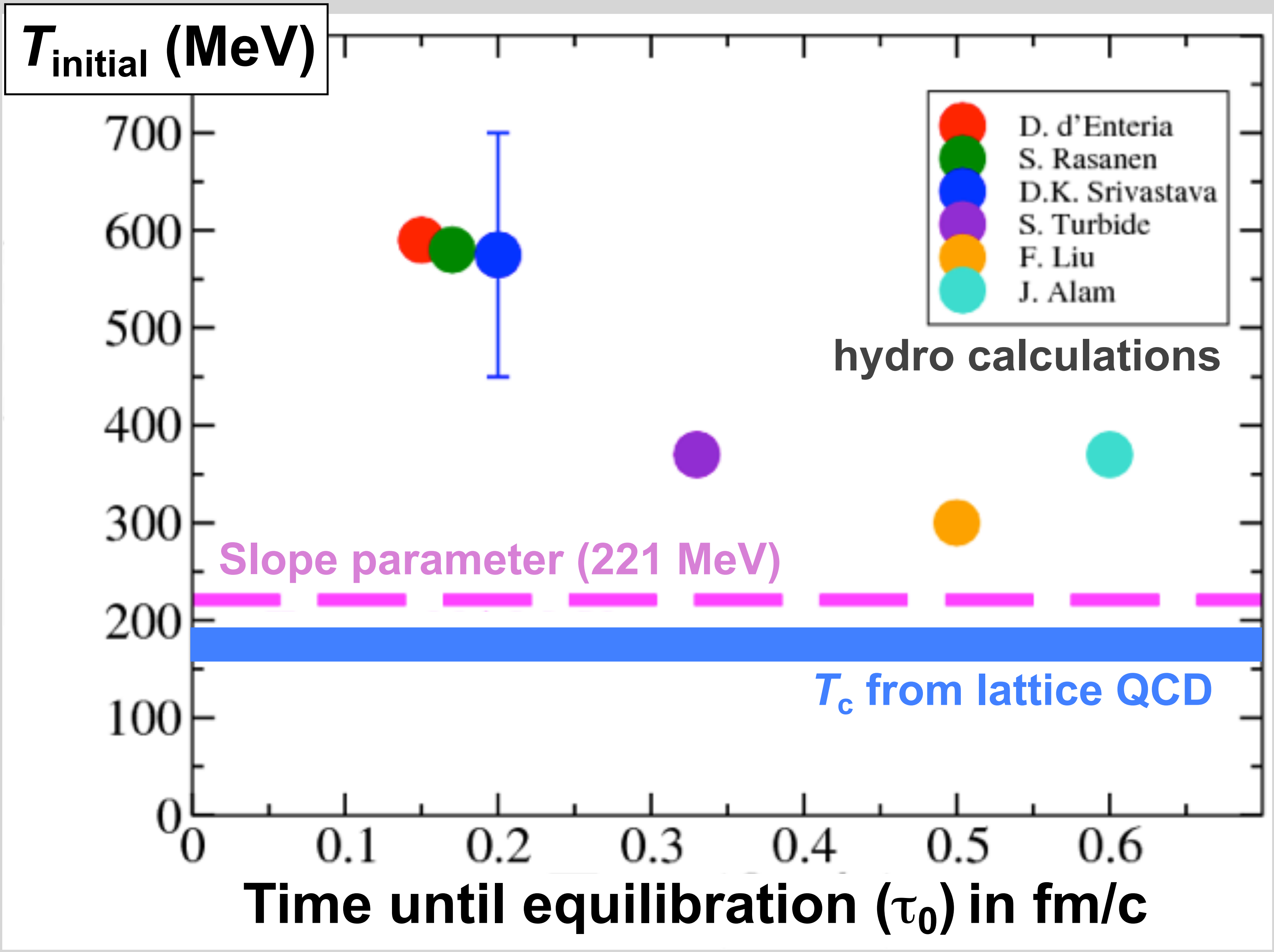


C. Gale, arXiv:0904.2184v1

- Model space-time evolution with ideal hydro
- This calculation (arXiv:0904.2184v1)
  - Hydro starts early (τ_0 = 0.2 fm/*c*) to take pre-equilibrium photons into account
  - Thermal equilibrium expected at τ_0 = 0.6 fm/*c* ($T_{initial}$ = 340 MeV)
  - Photons from jet-plasma interaction needed
- $T_{initial} > T_c \approx$ 170 - 190 MeV → evidence for the formation of a quark-gluon plasma

Similar conclusions for essentially all hydro models on the market

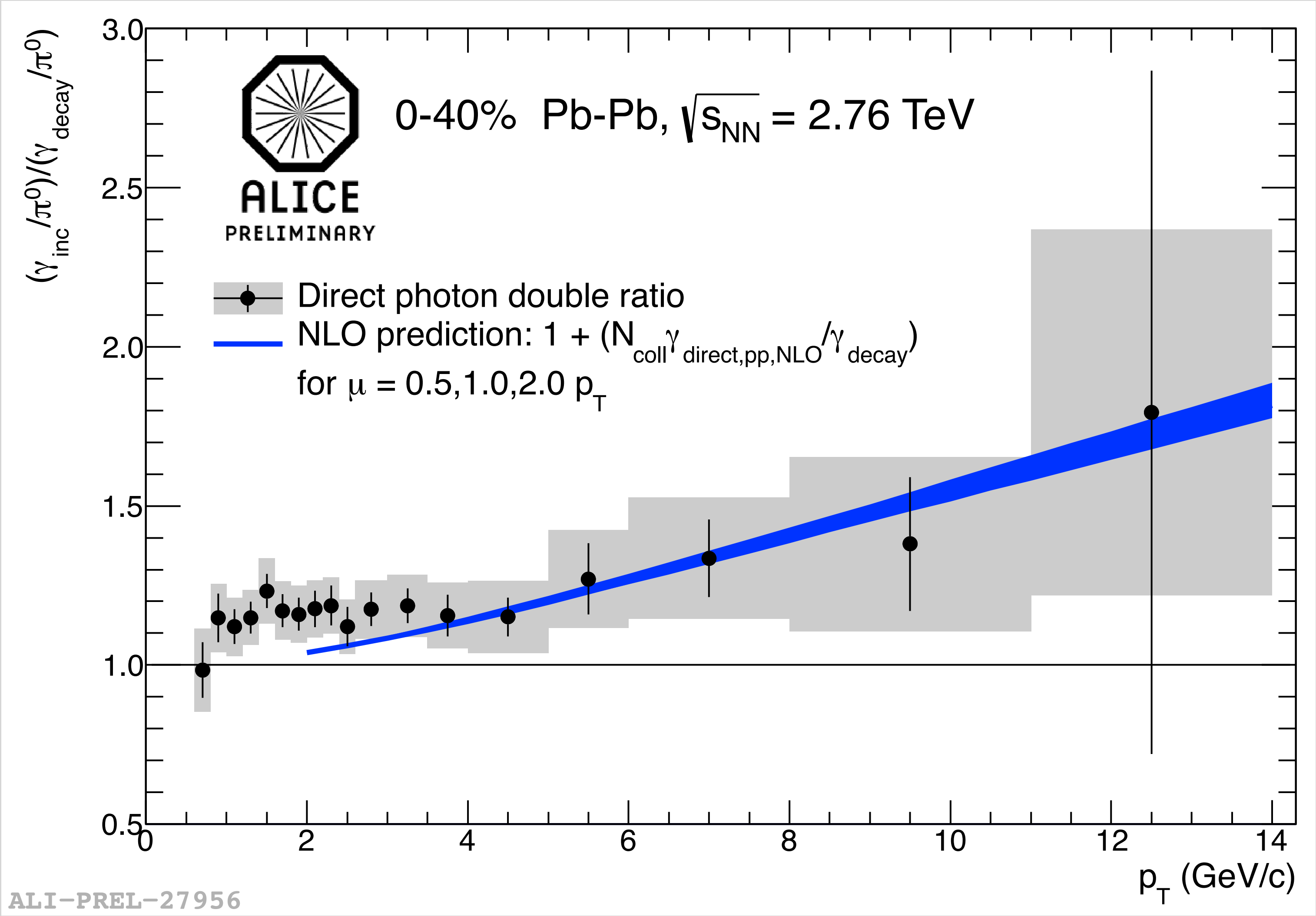
PHENIX Low p_T Direct Photon Data: Comparison with Different Hydro Models



Initial temperature above T_c in all models

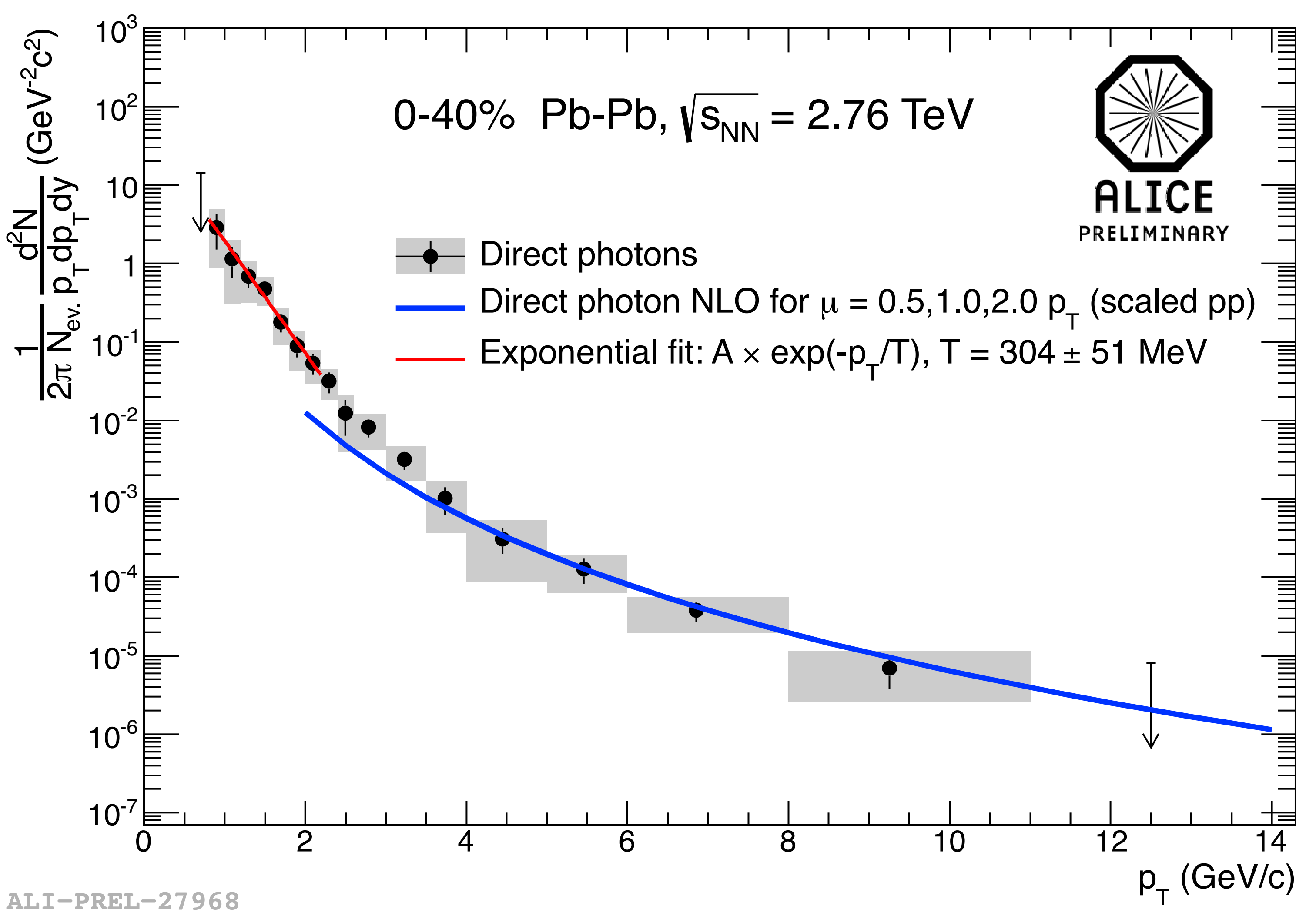
Thermal Photons at the LHC

- ALICE measurement through external conversion also done in Pb+Pb collisions
    - Remember: no significant excess in p+p collisions
    - Same in peripheral Pb+Pb: no significant direct γ signal
- In central Pb+Pb, ALICE observes significant direct photon signal
    - At low pT, signal is also significantly above NLO!
    - There appear to be additional (thermal) photons



Direct Photon Spectrum at the LHC

- With the double ratio, direct photon spectrum is calculated, here for central Pb+Pb
- At low pT, the measured spectrum is significantly above NLO calculation
- Use exponential fit to extract slope T from the spectrum:
  $f(p_T) = A \times \exp(-p_T/T)$
  (same fit as used by PHENIX)



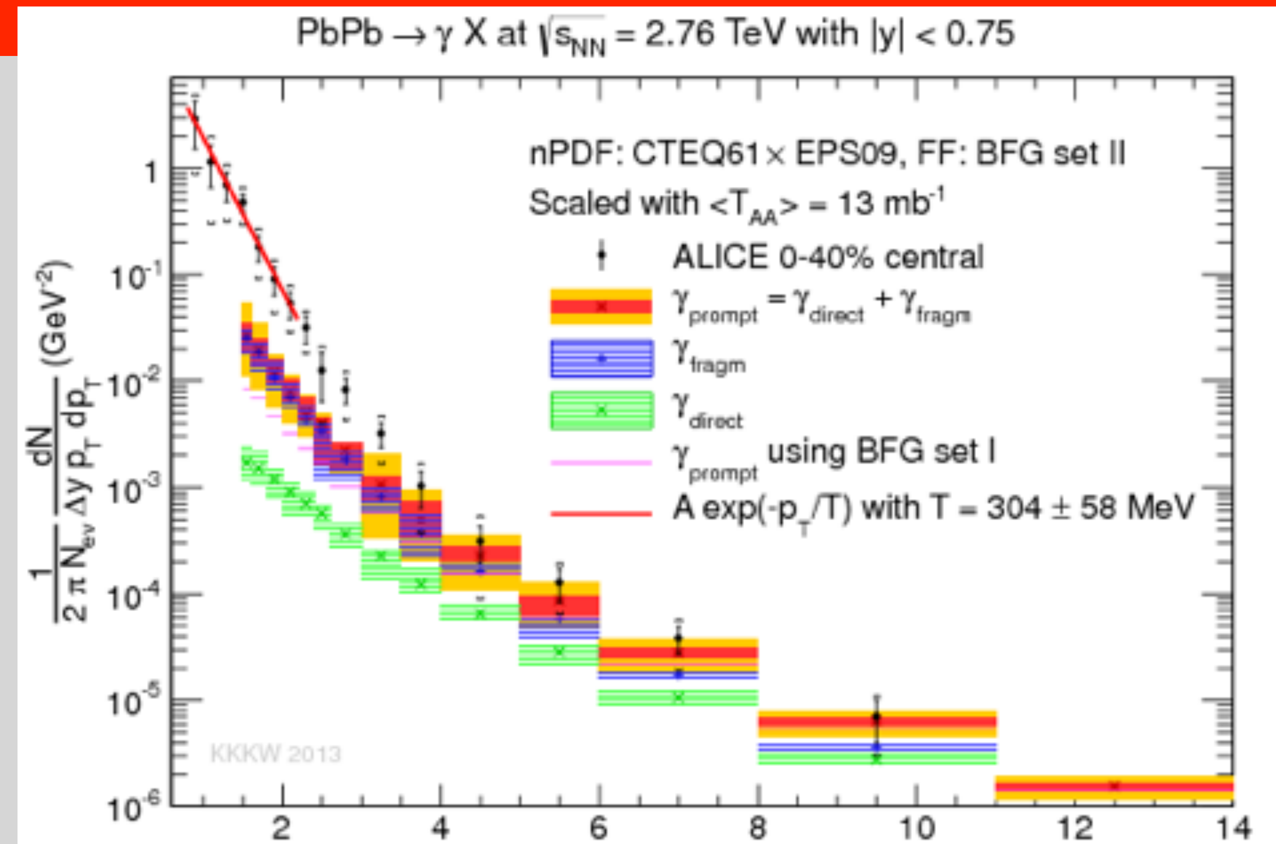
Slope parameter from exponential fit:
T = 304 ± 51 MeV

compare RHIC: T = 221±23±18 MeV

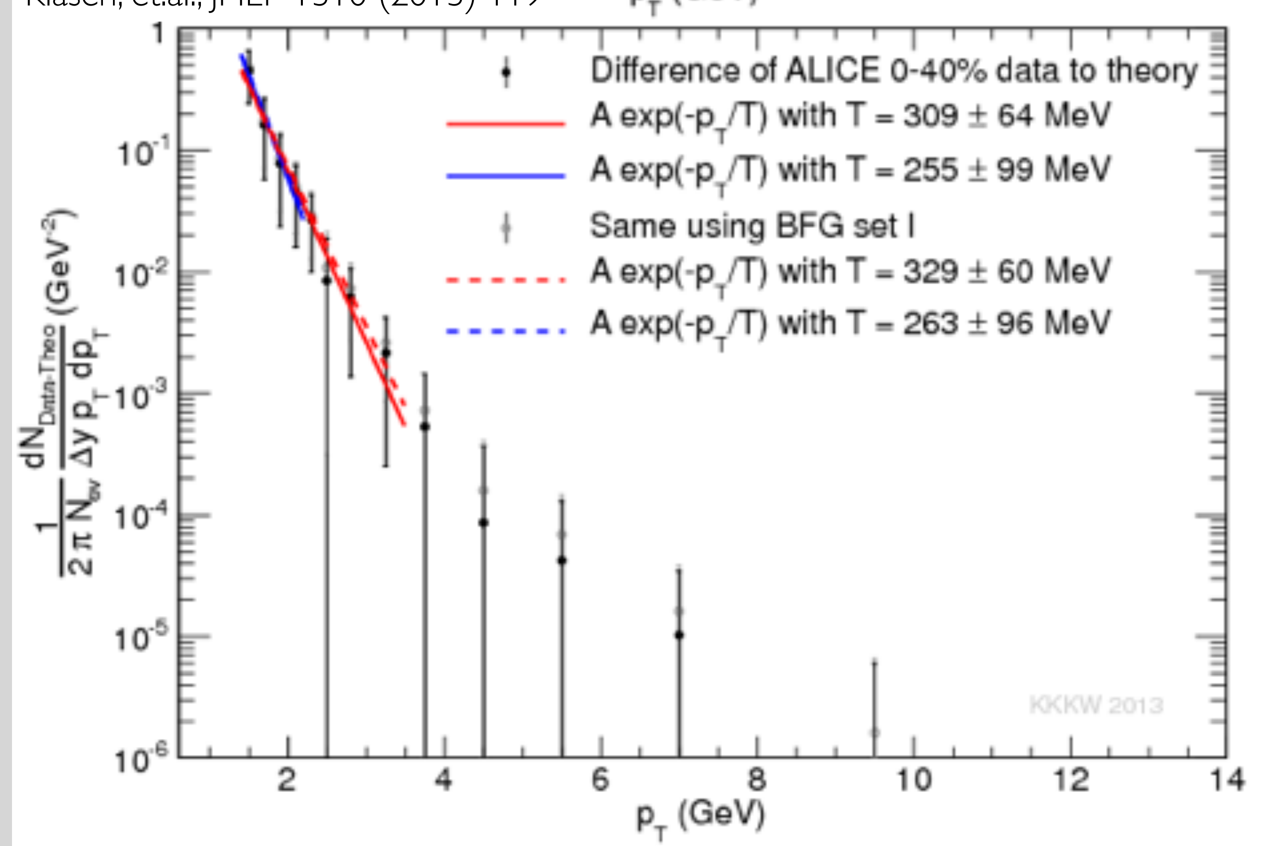
➡ T(LHC) > T(RHIC)

How Robust is the Thermal Interpretation?

- pQCD has uncertainties
- Study effect of uncertainties on slope parameter T
  - Subtract pQCD “background” from thermal signal, including theory uncertainty
  - Fit remaining thermal photon spectrum
- T parameter is very similar to ALICE fit (depending on the BFG set and fit range)
- Thermal signal remains!



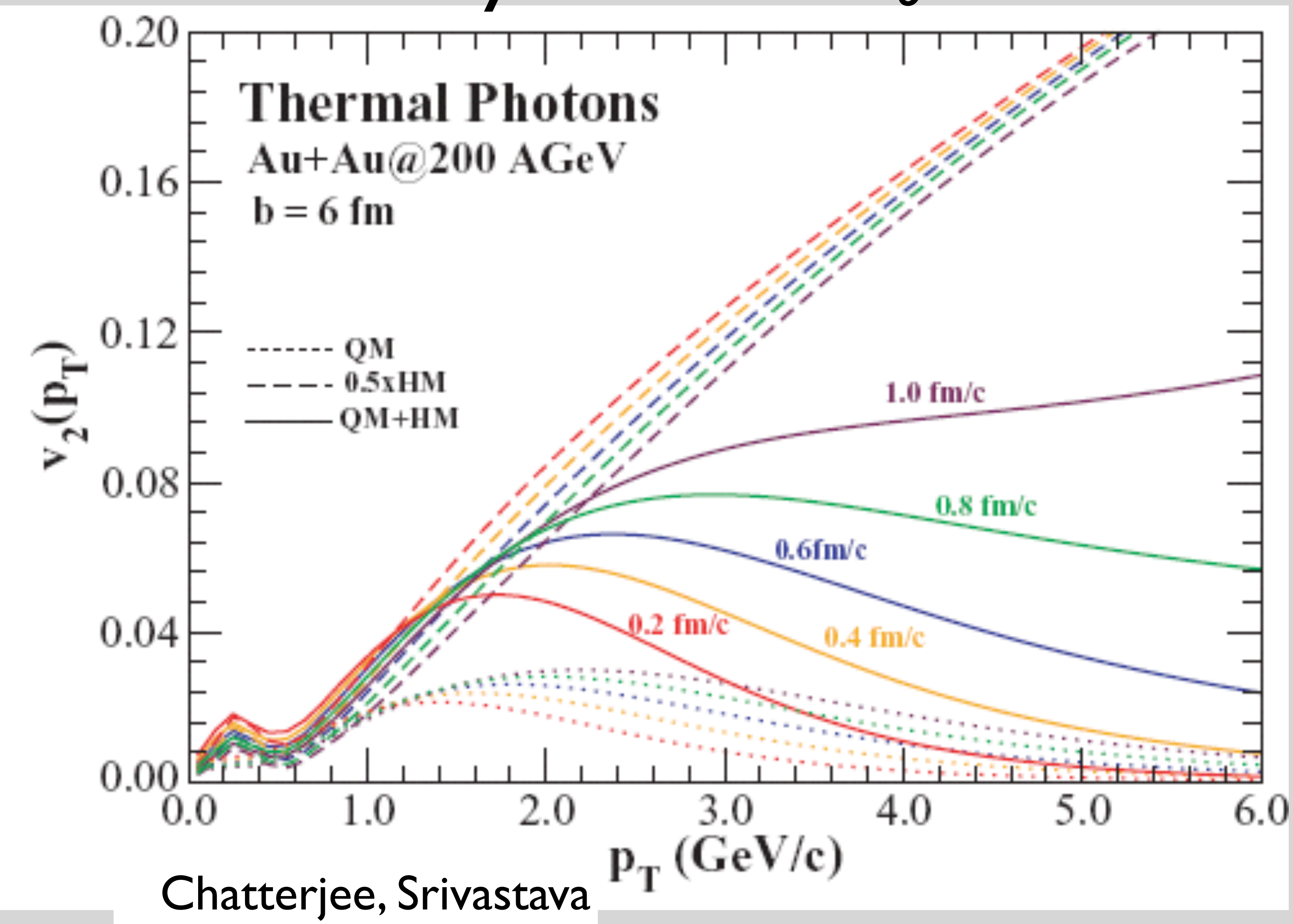
Klasen, et.al., JHEP 1310 (2013) 119



Direct Photon Flow

Direct photon v_2 further constrains T_i

Hydro after τ_0



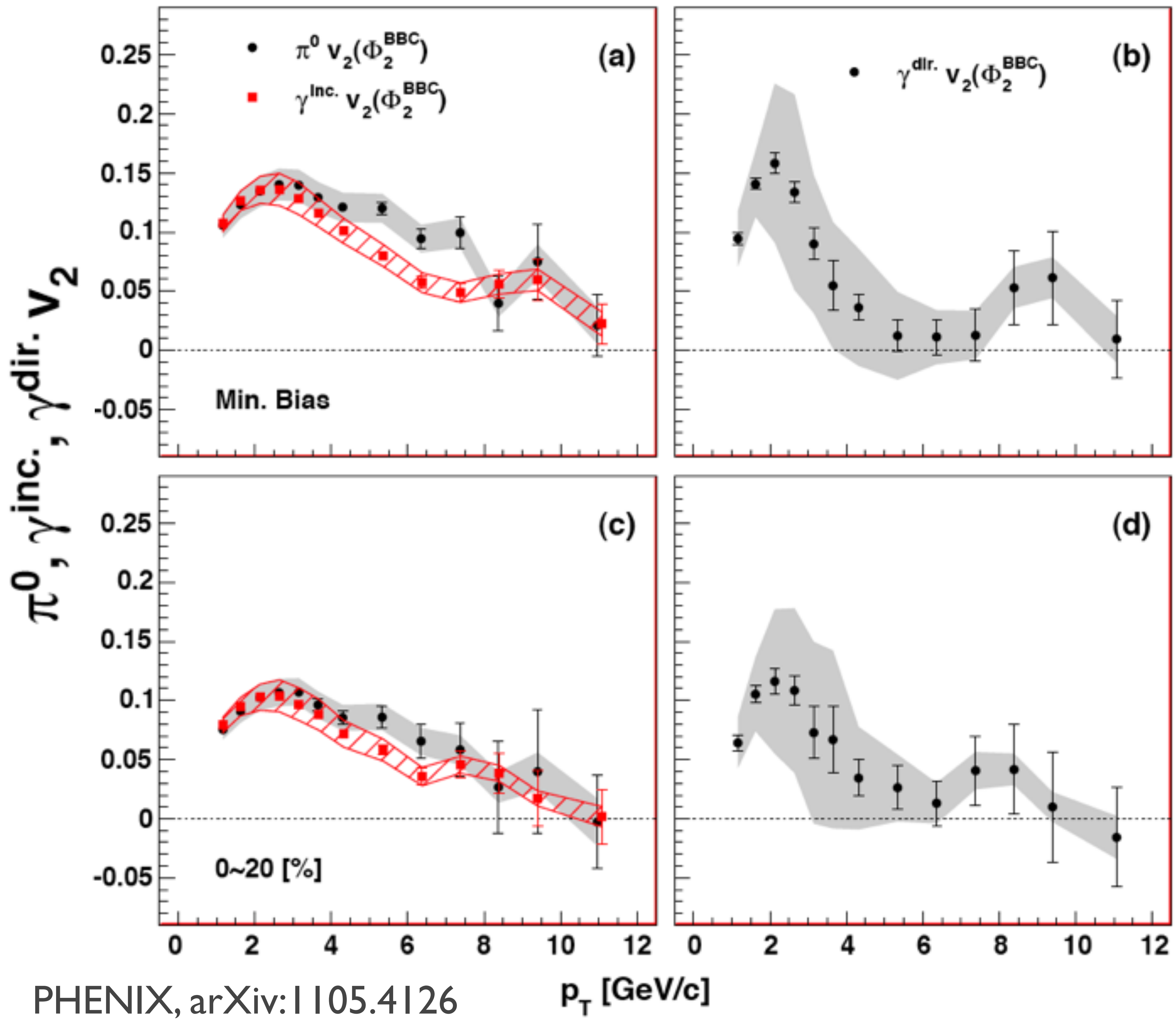
Chatterjee, Srivastava
PRC79, 021901 (2009)

- expected v_2 :
  - prompt photons: 0 (time zero)
  - thermal photons

early ↙ ↘ late

small (flow not built up)	large (like hadrons)

Significant Elliptic Flow of Direct Photons Found in Au+Au at 200 GeV for $p_T < 3$ GeV/c



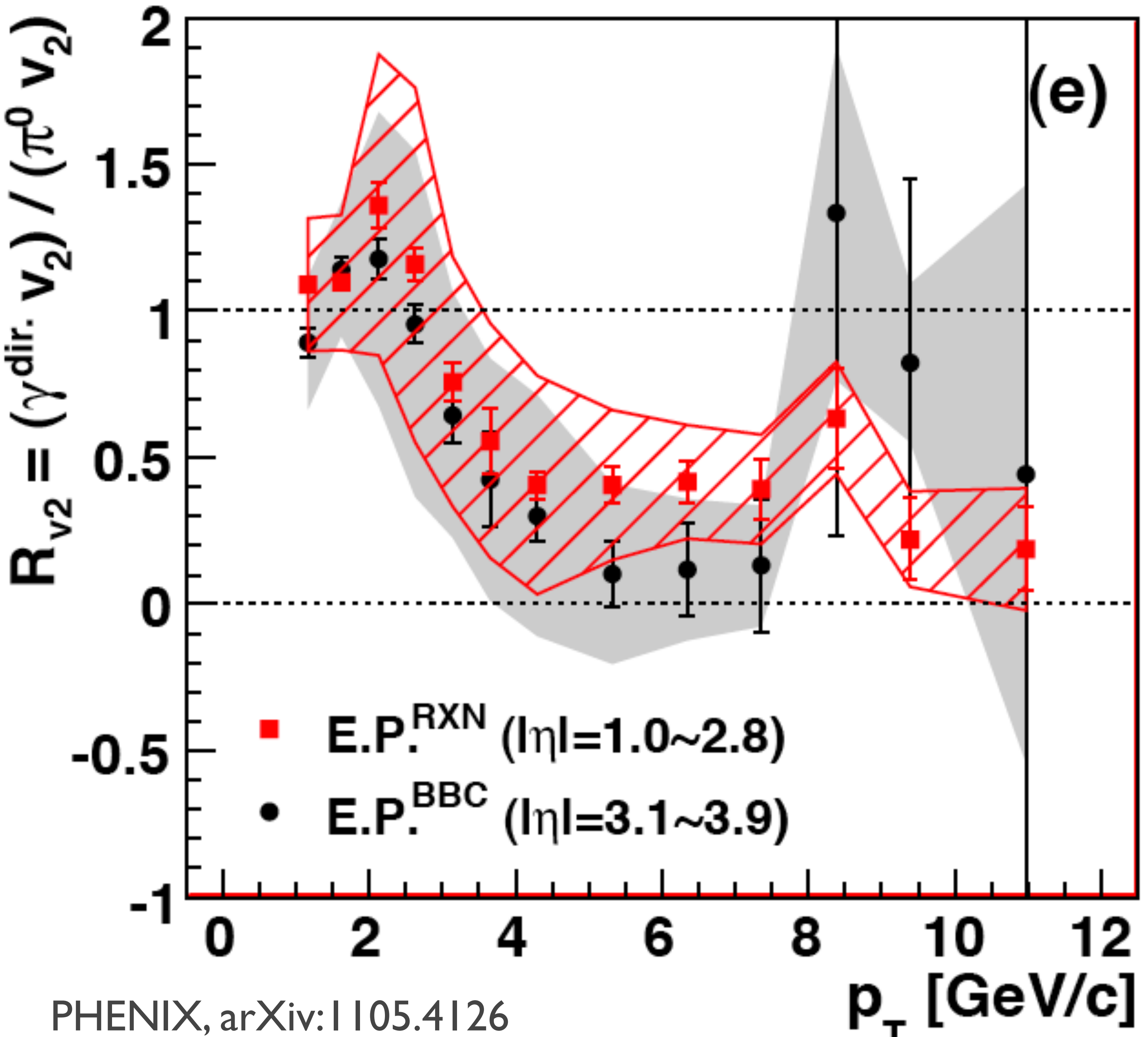
PHENIX, arXiv:1105.4126

$$v_2^{\mathrm{dir}} = \frac{R_\gamma v_2^{\mathrm{inc}} - v_2^{\mathrm{decay}}}{R_\gamma - 1}$$

$$R_\gamma = \frac{\gamma^{\mathrm{inc}}}{\gamma^{\mathrm{decay}}}$$

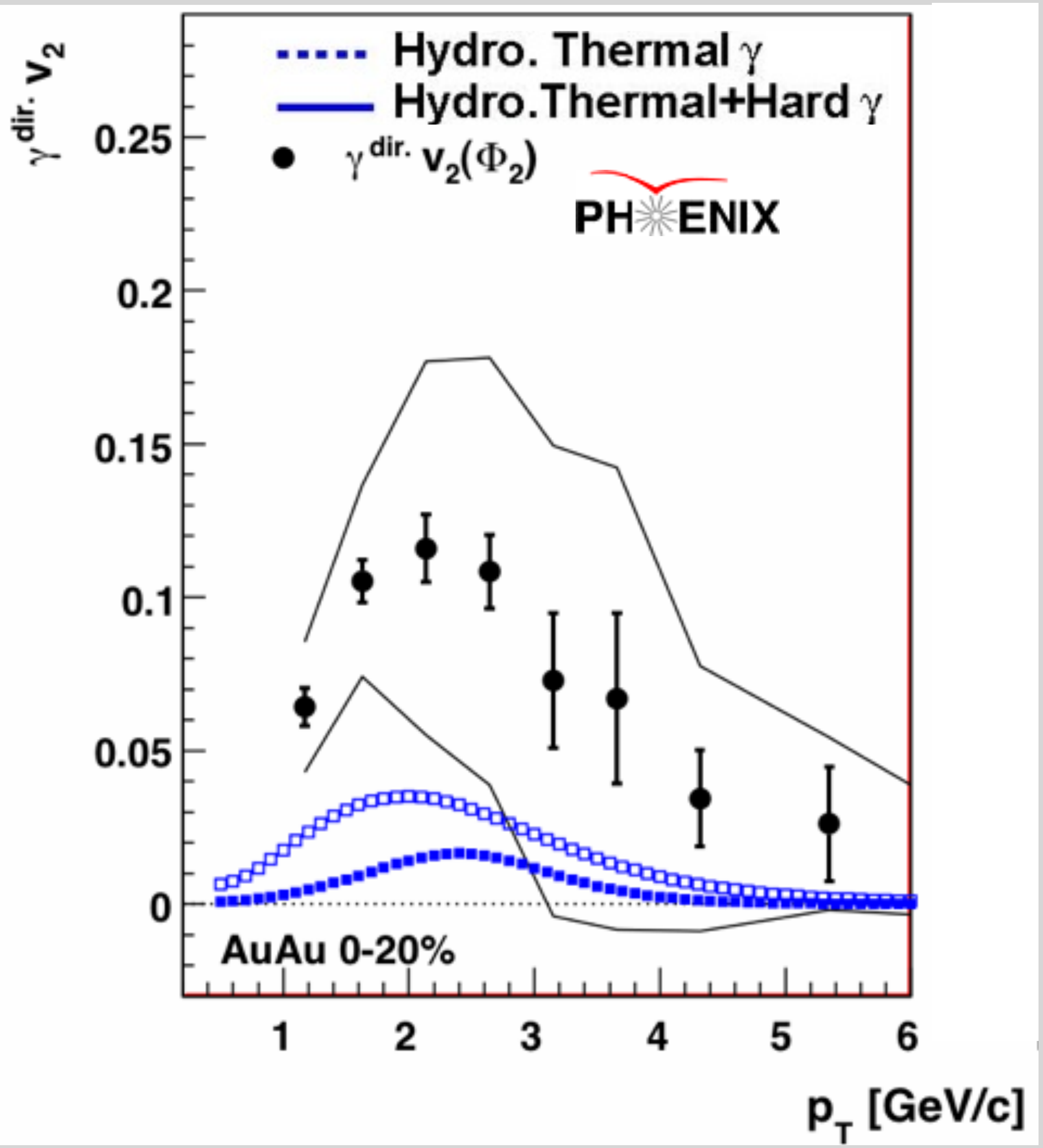
v_2^{inc} from calorimeter measurement

Direct Photon v_2 at p_T = 2 GeV/c as large as for Pions



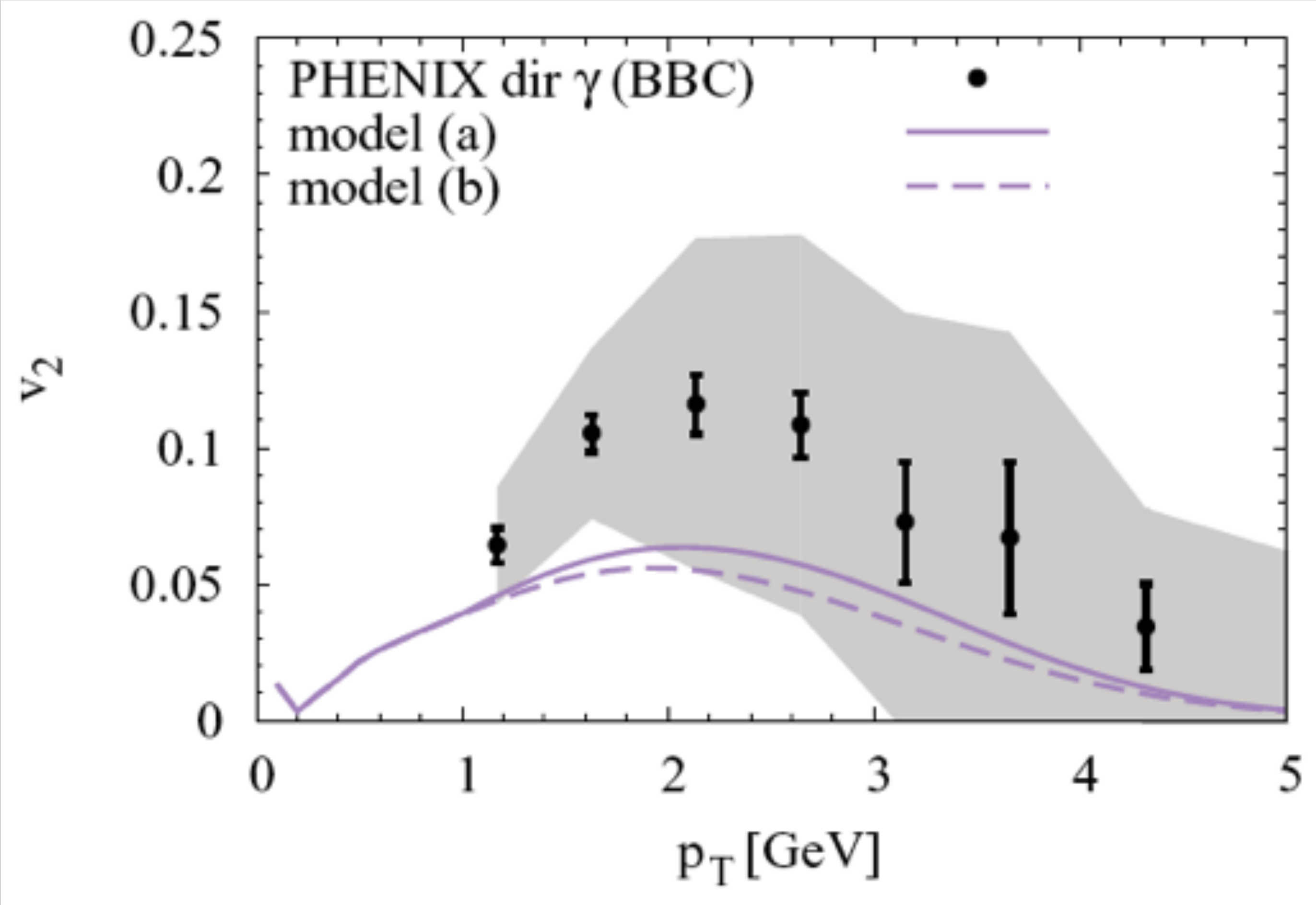
PHENIX, arXiv:1105.4126

Theory Comparison: A Big Puzzle (!?)



Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

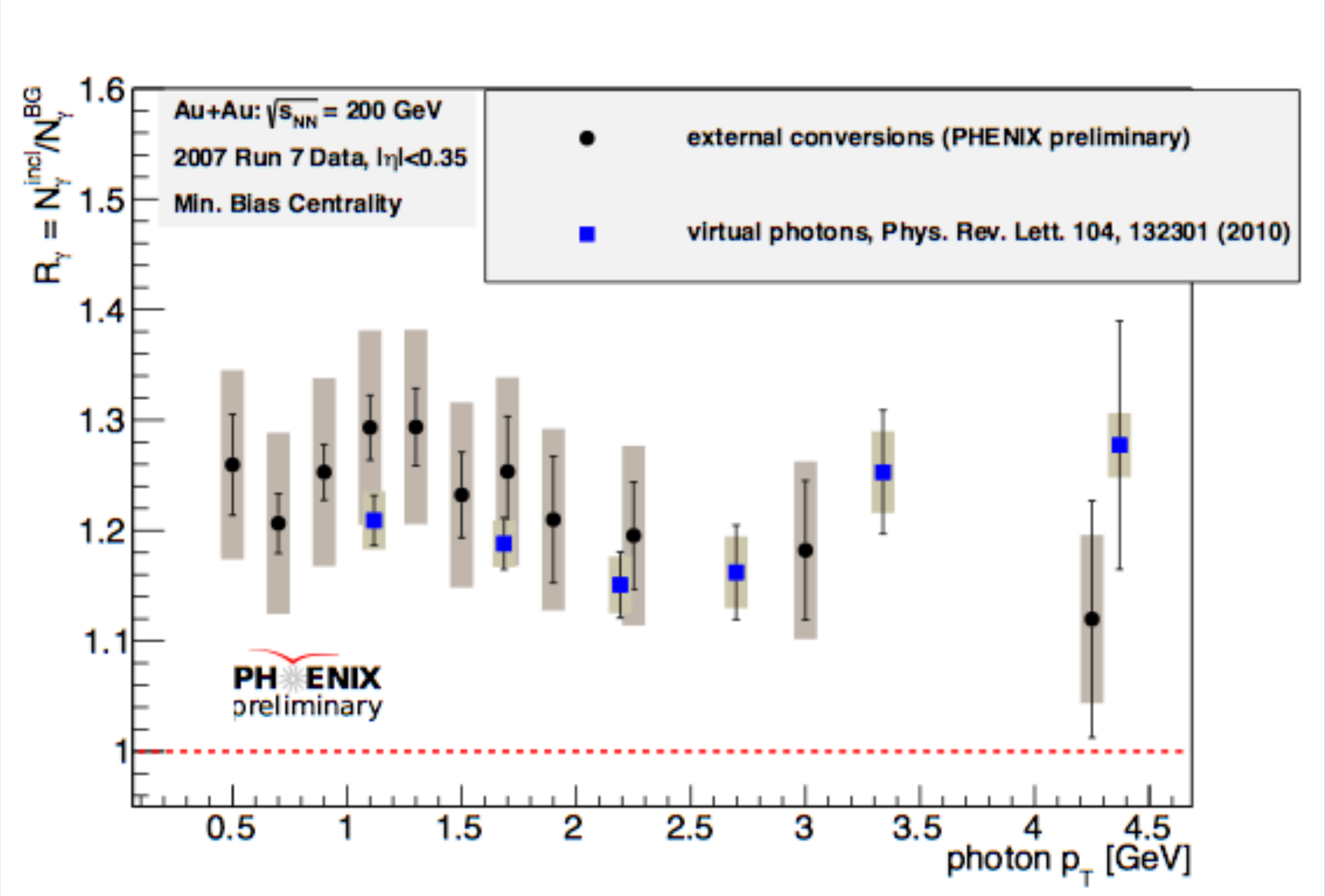
Hendrik van Hees, Charles Gale, Ralf Rapp,
Phys.Rev. C84 (2011) 054906



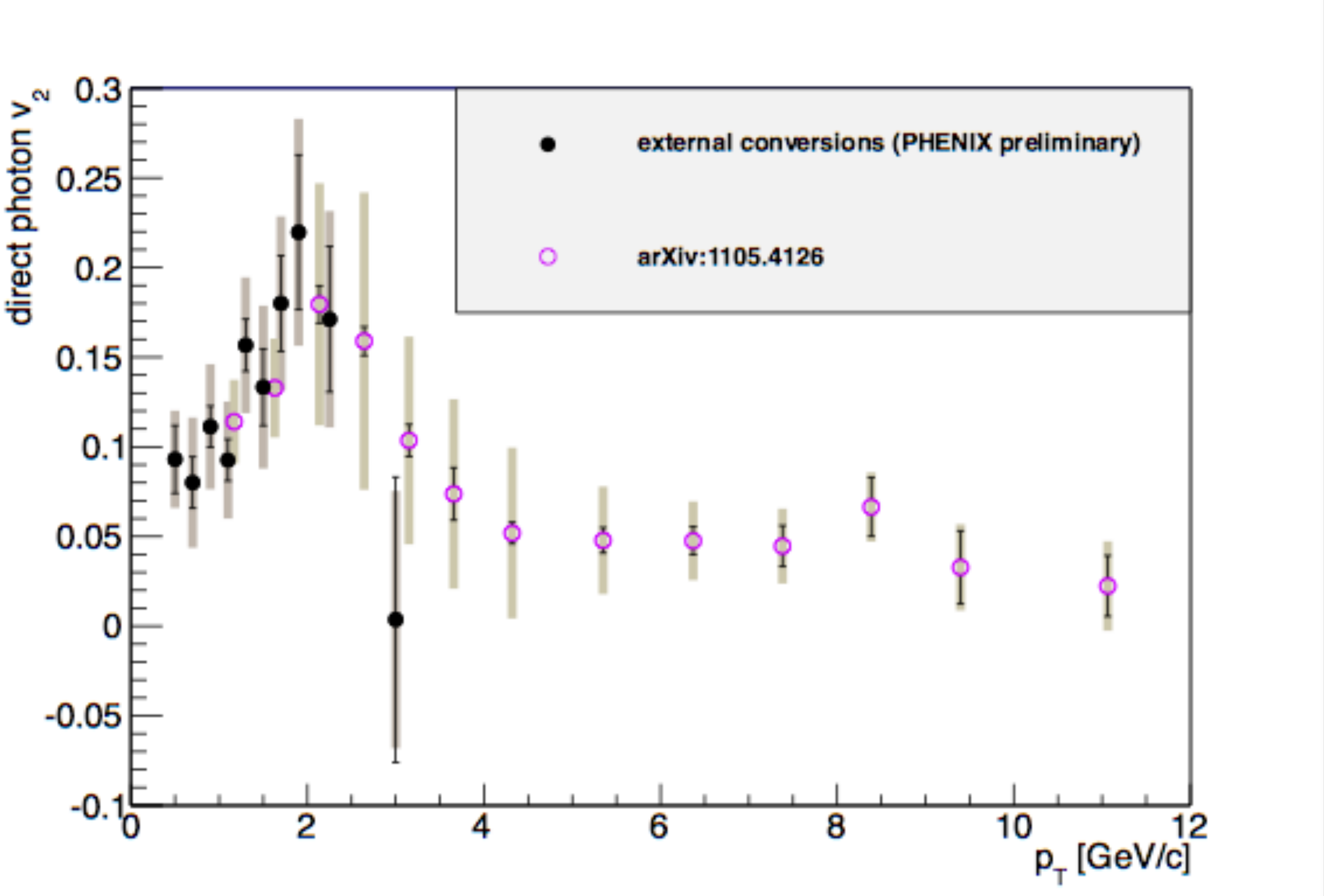
Slope of low p_T direct photons spectrum points to early emission, v_2 suggests late emission from mixed/hadronic phase

Cross Checks: External Conversion

- High direct photon v2 is an unexpected result
  - Is there a cross check?
  - Use different method: external conversion with alternate track model
- First thing to compare: R_γ
  - R_γ is necessary to calculate v_2
- R_γ is the same, systematic uncertainties are different



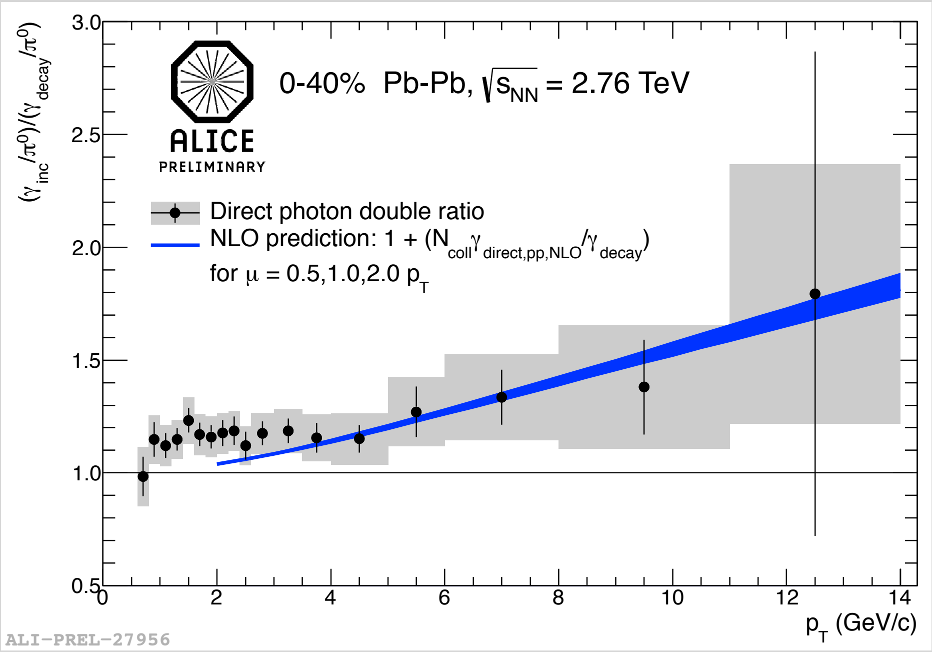
Compare v_2 for Different Methods



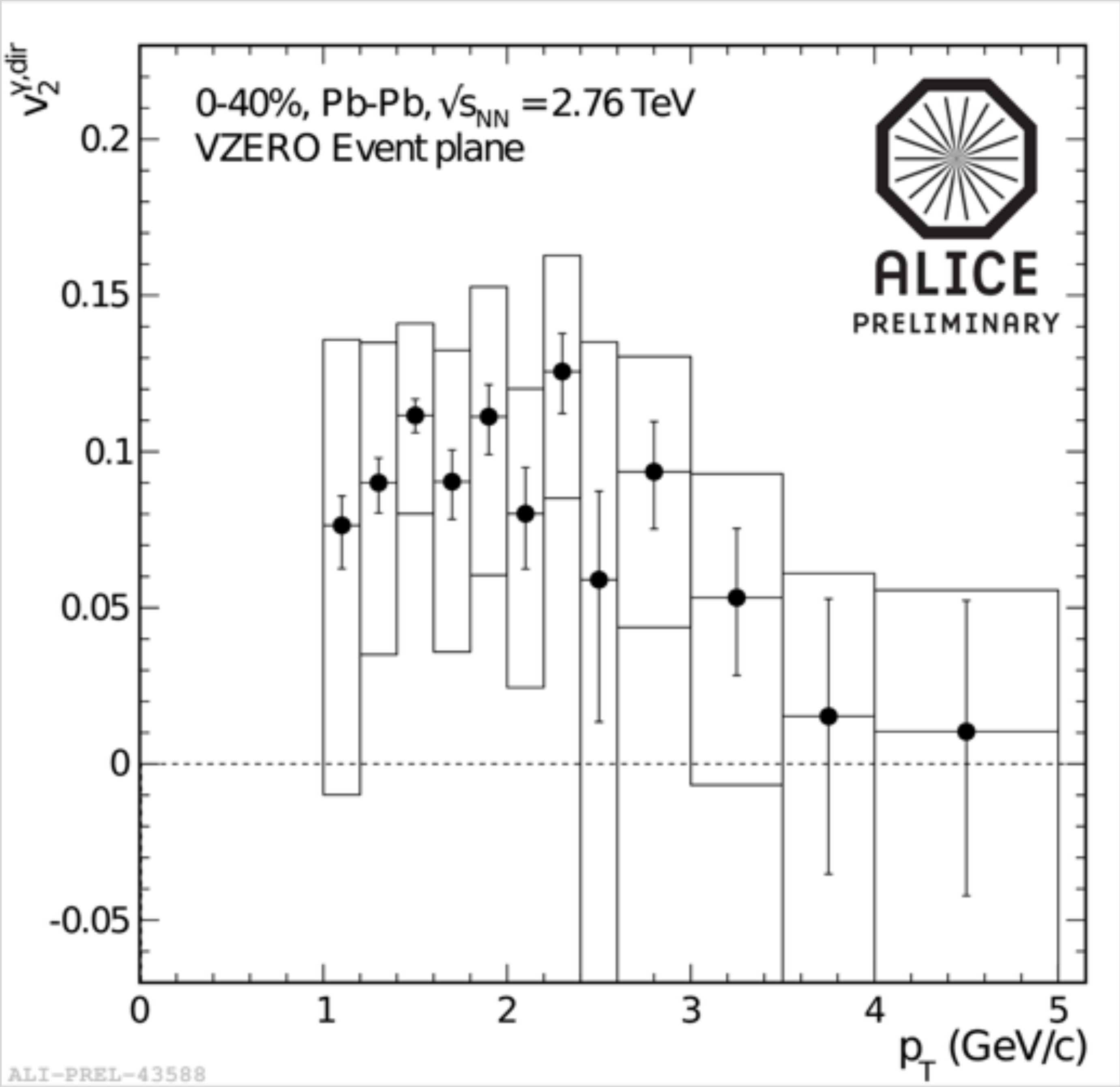
- PHENIX v_2 result is confirmed by the external conversion method
- Both internal and external cross checks are important in experiments!

LHC Enters the Game

- ALICE measured v2 of direct photons
- Similar size as in PHENIX
  - large systematic uncertainties
- Uncertainties driven by uncertainty on R_γ



- This measurement seems to support the "Direct Photon Puzzle"



Recent Developments?

- Direct photon v_2 and excess still not understood
- Are the measurements wrong? We hope not, but there are more and more cross checks coming
- What is missing in theoretical description?
  - Blue shift? Additional v_2 from interaction with hadrons? Anything else?
  - Ask your favourite theorist
- to be continued …

Thank You!